A STUDY OF LIQUID BEHAVIOR
IN A KUNDT'S TUBE

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SUMMARY

The general objective of this study was to investigate the phenomena associated with a tube partially filled with a liquid and subjected to a resonant acoustic field. Perhaps, however, the basic objective was to obtain a correlation which would predict the tube sound pressure level, SPL, at which liquid "curtains" form in a horizontal resonant tube containing a liquid. One sidelight of this study was an investigation to determine the commercial feasibility of employing the phenomena in a resonant tube containing a liquid for the desalinization of sea water.

The results of this investigation include extensive qualitative studies of the unusual behavior of liquids, liquid drops, smoke particles and particles in a liquid solution under resonant conditions at high sound pressure levels. Also included are parametric and experimental studies of curtains of liquids in various tubes, analytical and experimental studies of the pressure distribution in a resonant tube, and the results of the study to determine the feasibility of employing sound in the desalinization of sea water.

The qualitative studies present many interesting observations not previously reported in the literature, as well as a detailed description of numerous observed phenomena in the tube containing both liquid and smoke. Three liquids (water, acetone, and methyl alcohol), were studied, but most of the observations deal with water and acetone.

A correlation of the variables affecting curtain formation was obtained and it was found that excellent agreement was maintained with either water or acetone in the tube.

A proposed explanation for the basic change in the vortex patterns in a resonant tube first observed during 1960 by Jackson and Johnson[13] is given. This explanation suggests that the large vortices observed by these investigators are not the result of convection currents as has been suggested, but are the result of the excitation of vibration modes other than the usual transverse mode.

Several solutions for the pressure distribution in a resonant tube are given, including some unpublished solutions of Purdy[5,6]. It is shown that these solutions all give essentially the same results for the pressure distribution, and the conclusion is reached that the pressure distribution in a resonant tube, unlike the velocity, is not appreciably affected by higher order acoustical effects. Finally, these pressure solutions are compared with the measured values of the difference in height between a crest and a trough on the water surface and excellent agreement is obtained.

NOMENCLATURE

English Letters		Units
a	Constant	
b	Constant	
c	Isentropic Speed of Sound	ft/sec
C_p	Pressure Correction Factor, $14.69/p_\infty$	
D	Inside Diameter of Tube	in
d	Liquid Depth in Tube	in
db	Decibels	
F	Function	
f	Frequency	1/sec
f_1	Function	
f_2	Function	
f_3	Function	
f_4	Function	
f_5	Function	
f_6	Function	
k	Ratio of Specific Heats, c_p/c_v	
L	Length of Tube	ft
N	Number of Liquid Curtains Formed	
N_p	Number of Crests in Resonant Tube	
n	Exponent	
p	Pressure	lb/
P	Root-Mean-Square Pressure Deviation	lb/

NOMENCLATURE (Continued)

		Units
P_{max}	Absolute Value of the Maximum Pressure Deviation	lb/ft^2
R	Gas Constant	$ft^2/sec^2\text{-}^oR$
s	Entropy	$ft^2/sec^2\text{-}^oR$
SPL	Sound Pressure Level (re 0.0002 μ bars)	
t	Time	sec
T	Absolute Temperature	^oR
u	x-Component of Velocity	ft/sec
x	Space Coordinate	ft

Greek Letters

λ	Wave Length	ft
μ	Dynamic Viscosity	$lb\text{-}sec^2/ft^2$
π	3.14159	
ρ	Density	$lb/sec^2/ft^4$
σ	Surface Tension	lb/ft
ω	Circular Frequency	ft/ft-sec

Subscripts

o	Time Mean of a Property at x=0
∞	Time Mean or Undisturbed Value of a Property
max	Maximum Deviation from Time Mean (Pos.)
min	Maximum Deviation from Time Mean (Neg.)

Superscripts

'	Deviation from Time Mean of a Property

CHAPTER I

INTRODUCTION

Longitudinal Waves and the Kundt's Tube

A general knowledge of standing longitudinal waves and the Kundt's tube is necessary in order to follow the material presented herein. In addition, a limited amount of knowledge of the properties of an acoustic field is an aid in following the discussion in later chapters. For this reason and in order to make the presentation more self-sufficient, a general discussion of these topics will be presented.

When longitudinal waves are generated in a tube by an acoustic driver (loudspeaker horn) they behave in much the same way as transverse waves in a string. When these waves travel through a tube they are reflected at the end of the tube in much the same way that transverse waves traveling along the length of a string are reflected. When a transverse wave in a string reaches a fixed end, the displacement of the string must be zero. Thus the wave is reflected and a node is formed at the fixed end. Likewise, the closed end of a tube is a node since the particle displacement must be zero at this point. When the tube is closed, the reflected waves react with the waves traveling toward the closed end and, if the tube is in resonance, give rise to standing waves. If the end of the tube opposite the closed end is open or partially open the situation is not so clearly defined. The reflections at the open or partially open end of the tube may be such as to form an antinode (velocity antinode) at or near the opening. This, of course, is not the case for a string.

Standing waves (or resonance) are often demonstrated in the laboratory by an apparatus such as that shown in Figures 1 and 2. The apparatus shown in Figure 1 is usually known as a Kundt's tube* and consists of a clear glass or plastic tube closed at one end and driven at the open end by a loudspeaker. In order to demonstrate the presence of standing waves, a fine powder or cork dust is sprinkled on the floor of the tube. When the loudspeaker is tuned to a resonant frequency, the dust is swept to the nodes of the standing wave. Since the distance between these nodes is one-half wave length, the velocity of sound (i.e., the velocity of the wave in the tube) can be determined with reasonable accuracy. This type of demonstration yields a knowledge of standing velocity waves.

Standing pressure waves can be demonstrated with an apparatus such as that shown in Figure 2. This apparatus consists of a tube with an inlet for an inflammable gas and a row of small ports to allow the gas to escape and be ignited. The tube is closed at both ends. The driven end is usually closed by an elastic diaphragm (with the diaphragm being vibrated) or the horn of a driver is snugly fitted into a hole in a stopper and inserted into the open end.

When the tube is resonated and the gas escaping from the ports is ignited, a clear indication of the pressure variations within the tube is given by the variation in the size and color of the flame from port to port along the tube. That a pressure antinode occurs at points where

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* The origin of this name will become clear in Chapter II.

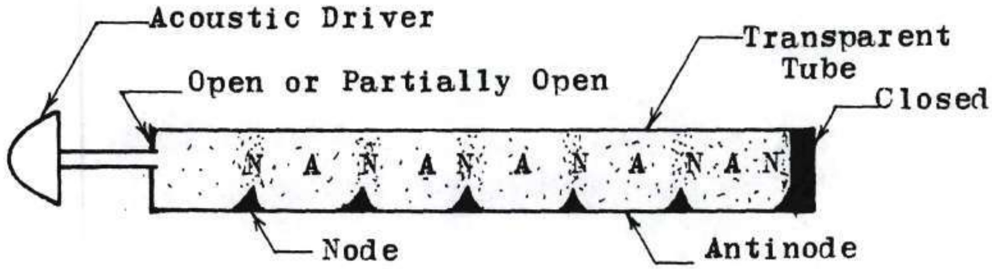


Figure 1. Kundt's Tube Containing Dust.

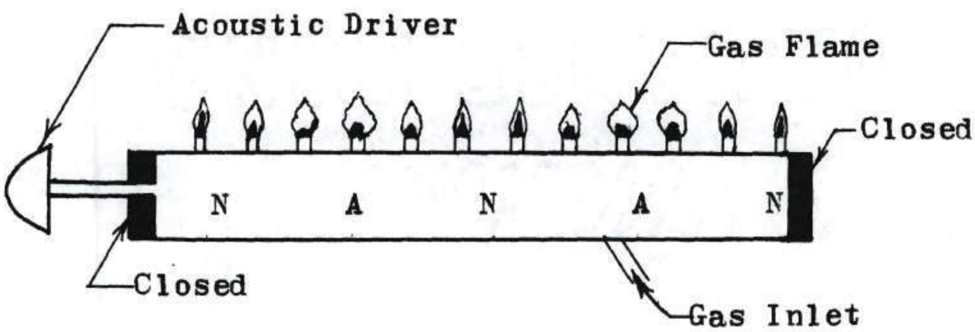


Figure 2. Kundt's Tube Containing a Gas.

velocity nodes occur is clearly demonstrated by the fact that the flames near the closed end of the tube are small in comparison with the flames a quarter wave length away. This indicates that the pressure variations above and below the average are a maximum at the velocity nodes and that there are no pressure variations at the antinodes. This becomes understandable when one considers that the masses of gas on opposite sides of a node are vibrating in opposite phase. Therefore, when these masses move toward each other the pressure increases to a maximum, and, when they move away, the pressure decreases to a minimum. On the other hand, masses of gas on each side of an antinode move in phase and thus cannot yield a pressure rise. The pressure distribution in an acoustic field is discussed in detail in Appendix A.

Resonant Acoustic Fields - Mathematical Description

The gross behavior of a one-dimensional acoustic field can be satisfactorily explained by a first order analysis. Such an analysis gives accurate results for the velocity of a plane wave front as well as pressure and density variations along a tube and variations of these quantities about their mean values at a point in the tube. An analysis of this type can be understood from a study of Chapters I and VI of the book by C. A. Coulson[1].

Higher-order effects indicating the existence of secondary flows (stationary vortices) have been examined by Rayleigh[2,3], Westervelt[4], Purdy[5] and Purdy, et al.[6] and will be discussed further in Chapters II and IV and in Appendix A. Photographic evidence of the existence of these secondary effects in a resonant tube has been obtained by many investigators. Figure 3 is a typical photograph obtained by Jackson and Johnson[7] which clearly shows the stationary vortices by the use of cigarette smoke in a resonant tube. The circulation is also indicated schematically in Figure 4.

The method of obtaining the wave equations describing the motion of plane waves traveling at the acoustic velocity along with the pressure, velocity and density variations will now be outlined. The special case for a tube closed at one end will be examined.

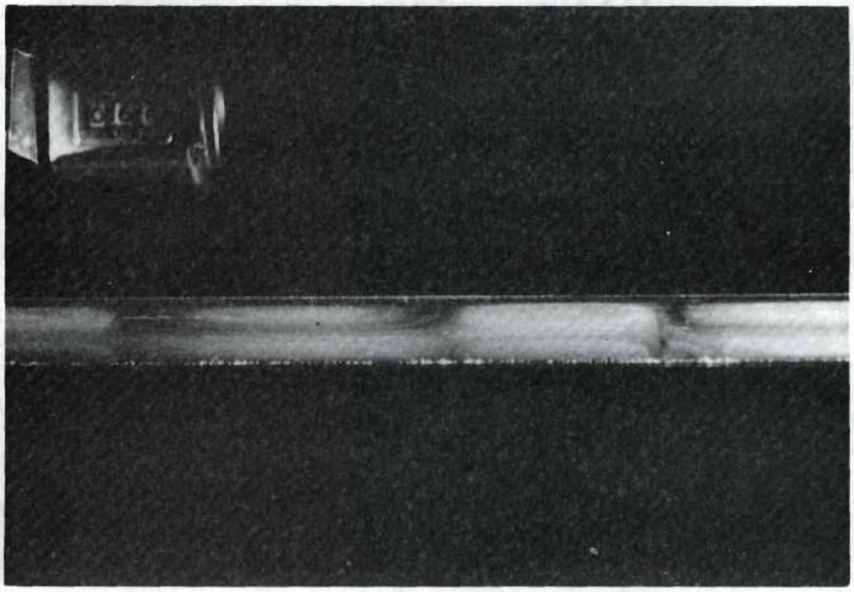
Model of the Acoustic System

The idealized model to be employed in representing the acoustic field will be a frictionless, perfect gas contained between parallel plates and excited at the point x = 0 in such a manner that plane waves travel down the tube from this point (see Figure 5).

Figure 5. Acoustic System.

Mathematical Description of Plane Waves

Most texts dealing with the subject of fluid mechanics or gas dynamics show that a small velocity or pressure disturbance is propagated at the isentropic speed of sound. For a perfect gas, this velocity of propagation is given by



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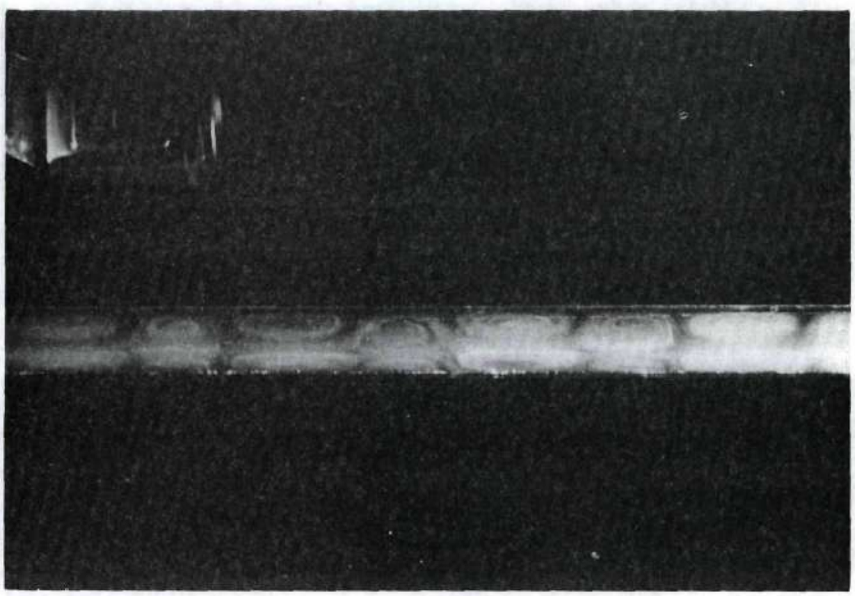

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Figure 3. Rayleigh-Andrade Cells Obtained by Jackson and Johnson in a Resonant Tube.

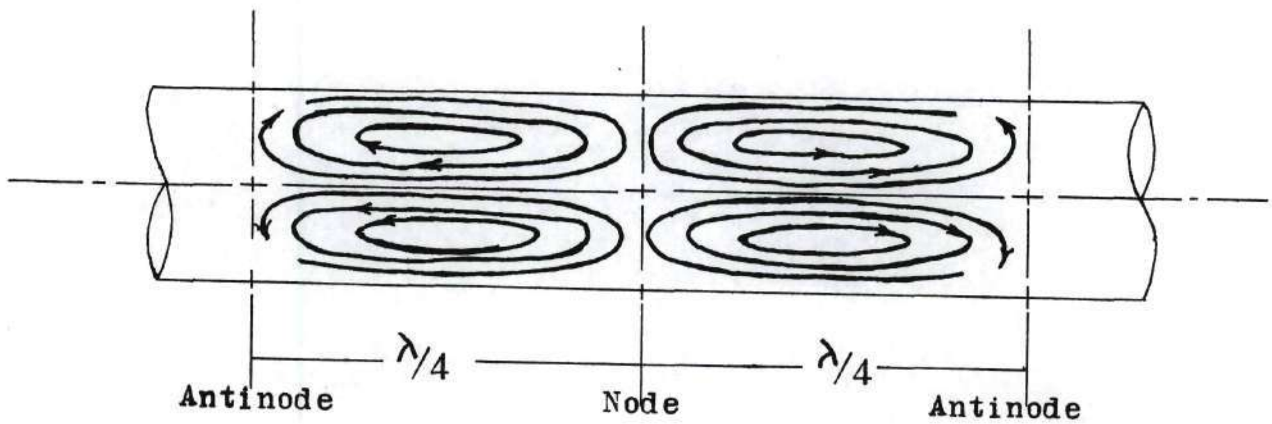

Figure 4. Schematic of Rayleigh-Andrade Vortices.

$$c^2 = \left.\frac{\partial p}{\partial \rho}\right]_s = kg_oRT = kg_op/\rho \tag{1-1}$$

where the subscript, s, indicates that the derivative is taken at constant entropy. (The process taking place in the wave was shown to be essentially isentropic by Laplace in his famous correction of Newton's isothermal assumption.) A wave traveling at this velocity is shown in Figure 5. It should be noted that waves reflected from the closed end of a tube give rise to waves traveling in the negative x-direction. Thus, it is possible to have waves moving in both the positive and negative x-directions.

The behavior of these plane waves (which are constrained to move only in the x-direction) is governed by the one-dimensional wave equation. The derivation of the wave equation will be outlined at this point. Further discussions of various aspects of the wave equation can be found in References(1)(5)(6)(7)(8)(9) and (10).

It is anticipated that the equation governing the motion of a plane wave should result in an equation of the form:

$$u = f(x,t) \ . \tag{1-2}$$

The basic equations from which the wave equation is to be obtained are:

Momentum

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial x} + \frac{\partial p}{\partial x} = 0 \tag{1-3a}$$

Continuity

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u) = 0 \tag{1-3b}$$

Equation of State for a Perfect Gas

$$\rho = \rho RT \qquad (C_p, R \text{ constants}) \qquad (1\text{-}3c)$$

Second Law of Thermodynamics

$$s = \text{constant} \qquad (1\text{-}3d)$$

Equation (1-3d) along with the assumption of a perfect gas implies that a relation between pressure and density of the form

$$p/\rho^k = \text{constant} \qquad (1\text{-}4)$$

exists.

By definition, an acoustic wave produced only small perturbations in the values of properties from their time-mean or undisturbed values. Thus, the velocity, pressure and density can be expressed as a linear sum of their time-mean property values and the deviation from the time-mean values produced by the acoustic wave

$$u = u_\infty + u' , \qquad (1\text{-}5a)$$

$$p = p_\infty + p' \qquad (1\text{-}5b)$$

and

$$\rho = \rho_\infty + \rho' , \qquad (1\text{-}5c)$$

where u_∞, p_∞, and ρ_∞ are the time-mean values of the velocity, pressure and density, respectively, and u', p' and ρ' are the deviations of these values from the time-mean and are functions of both time and position.

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$$c^2 = \frac{dp}{d\rho} = \left[\frac{dp}{d\rho}\right]_\infty + \left[\frac{d^2p}{d\rho^2}\right]_\infty (\rho' - \rho_\infty) + \ldots \qquad (1\text{-}6e)$$

Making use of the isentropic relation

$$p = p_\infty \, (\rho/\rho_\infty)^k \, , \qquad (1\text{-}6f)$$

yields

$$\left[\frac{dp}{d\rho}\right]_\infty = \left[k \; p_\infty \; \rho^{k-1} \; \rho_\infty{}^{-k}\right]_\infty \qquad (1\text{-}6g)$$

and

$$\left[\frac{d^2p}{d\rho^2}\right]_\infty = (k-1) \; c_\infty{}^2/\rho_\infty \qquad (1\text{-}6h)$$

Substitution of (1-6g) and (1-6h) into (1-6e) then yields a relation for c^2

$$c^2 = c_\infty{}^2 \left[1 + (k-1) \; \rho'/\rho_\infty + \text{-------}\right], \qquad (1\text{-}6i)$$

where all higher order terms in ρ'/ρ_∞ are to be omitted in this first-order analysis.

<u>Step III.</u> Substitute (1-6a) and the partial derivative of (1-6i) with respect to t into (1-6c) to obtain the following first-order approximation:

$$\frac{\partial^2 p}{\partial t \partial x} = -c^2 \frac{\partial^2}{\partial x^2} (\rho u) + \frac{c_\infty^2 \; (k-1)}{\rho_\infty} \frac{\partial \rho}{\partial x} \frac{\partial \rho'}{\partial t} \, . \qquad (1\text{-}7)$$

Step IV. From the momentum equation, determine $\frac{\partial p}{\partial x}$. Next, differentiate this to obtain

$$\frac{\partial^2 p}{\partial t \partial x} = - \frac{\partial}{\partial t} (\rho \frac{\partial u}{\partial t}) - \frac{\partial}{\partial t} (\rho u \frac{\partial u}{\partial x}) . \tag{1-8}$$

Step V. Equate the expressions for $\frac{\partial^2 p}{\partial t \partial x}$ given in (1-7) and (1-8) to obtain

$$\frac{\partial^2 u}{\partial t^2} - c^2 \frac{\partial^2 u}{\partial x^2} = \frac{c^2 u}{\rho} \frac{\partial^2 \rho}{\partial x^2} - \frac{c_\infty^2 (k-1)}{\rho \ \rho_\infty} \frac{\partial \rho}{\partial x} \frac{\partial \rho'}{\partial t}$$

$$- \frac{1}{\rho} \frac{\partial \rho}{\partial t} \frac{\partial u}{\partial t} - \frac{1}{\rho} \frac{\partial}{\partial t} (\rho u \frac{\partial u}{\partial x}) . \tag{1-9}$$

The equation to the left of the equality is the desired wave equation.

Step VI. The final step consists of showing that the individual terms on the right side of (1-9) are of order δ when compared to the terms on the left side of the equation (which can be shown to be of order 1). A masterly presentation of the order analysis for this case is given by Purdy(5). This order analysis leads to the desired wave equation

$$\frac{\partial^2 u}{\partial t^2} - c_\infty^2 \frac{\partial^2 u}{\partial x^2} = 0 \tag{1-10}$$

where c_∞ has been substituted for c by virtue of the first-order assumption.

Other techniques dealing with the reduction of (1-9) to the form of

(1-10) are usually related to neglecting higher order terms in a power series expansion of the properties of the flow. Sanders[7] employs such a technique.

It should be noted that a similar analysis for pressure waves and density waves can be obtained in a manner analogous to that employed in Step I through Step VI. The results of such an analysis are

$$\frac{\partial^2 p}{\partial t^2} = c_\infty^2 \frac{\partial^2 p}{\partial x^2} \tag{1-11a}$$

and

$$\frac{\partial^2 \rho}{\partial t^2} = c_\infty^2 \frac{\partial^2 \rho}{\partial x^2} \quad . \tag{1-11b}$$

The final forms of the equations for velocity, pressure, and density are obtained when it is noted that since u_∞ is zero and both p_∞ and ρ_∞ are constants, substitution of (1-5a) into (1-10), (1-5b) into (1-11a) and (1-5c) into (1-11b) results in

$$\frac{\partial^2 u'}{\partial t^2} = c_\infty^2 \frac{\partial^2 u'}{\partial x^2} \ , \tag{1-12a}$$

$$\frac{\partial^2 p'}{\partial t^2} = c_\infty^2 \frac{\partial^2 p'}{\partial x^2} \tag{1-12b}$$

and

$$\frac{\partial^2 \rho'}{\partial t^2} = c_\infty^2 \frac{\partial^2 \rho'}{\partial x^2} \tag{1-12c}$$

These equations yield the variation of velocity, pressure and density repectively from their time-mean values as a function of both position and time.

The general solutions of the velocity, pressure and density wave equations written to include both leftward plane waves and rightward plane waves are of the form

$$u'(x,t) = f_1\ (x - c_\infty t) + f_2\ (x + c_\infty t)\ , \tag{1-13a}$$

$$p'(x,t) = f_3\ (x - c_\infty t) + f_4\ (x + c_\infty t) \tag{1-13b}$$

and

$$p'(x,t) = f_5\ (x - c_\infty t) + f_6\ (x + c_\infty t)\ , \tag{1-13c}$$

where f_1, f_2, f_3, f_4, f_5, and f_6 are arbitrary functions of their arguments. In addition, and since the time-mean value of $u(x,t)$ is zero, it follows from (1-5a), (1-5b) and (1-5c) that the value of $u(x,t)$ is determined by (1-13a) alone and that the values of $p(x,t)$ and $\rho(x,t)$ are determined merely by adding their "stagnation" or "no-sound" values to (1-13b) and (1-13c), respectively.

Solution for the Resonant Tube

The solution for the resonant tube is now obtained by the method of D'Alembert*. For this solution, it will be assumed that the waves in the tube are generated by a simple harmonic vibration at the point $x=0$ such that

$$u'(0,t) = -U_o \cos(\omega t) \tag{1-14}$$

* This classical method of solution can be found in any standard text of higher mathematics.

where U_o is the maximum particle velocity at the driven end of the tube.

The solution can be written

$$f_1(x-c_\infty t) = -\frac{U_o}{2}\left[\cos\left(\frac{\omega x}{c_\infty}\right)\cos(\omega t) + \sin\left(\frac{\omega x}{c_\infty}\right)\sin(\omega t)\right] \quad (1\text{-}15a)$$

$$f_2(x+c_\infty t) = -\frac{U_o}{2}\left[\cos\left(\frac{\omega x}{c_\infty}\right)\cos(\omega t) - \sin\left(\frac{\omega x}{c_\infty}\right)\sin(\omega t)\right] \quad (1\text{-}15b)$$

Substitution of these functions into (1-13a) yields

$$u'(x,t) = -U_o\left[\cos\left(\frac{\omega x}{c_\infty}\right)\cos(\omega t)\right] \; . \quad (1\text{-}16)$$

By definition, the wave length, λ, is the value of x for which the velocity completes one cycle, or

$$\frac{\omega x}{c_\infty} = 2\pi \; ; \quad (1\text{-}17a)$$

therefore, λ is given by

$$\lambda \equiv \frac{2\pi c_\infty}{\omega} = \frac{c_\infty}{f} \quad (1\text{-}17b)$$

where the circular frequency, ω, is related to the cyclic frequency, f, through the equation

$$\omega = 2\pi f \; . \quad (1\text{-}17c)$$

Equation (1-16) thus indicates that the maximum amplitude of the velocity at any point in the tube is given by

$$\left| u'_{max} \right| = U_o \cos(\omega x/c_\infty) \ , \tag{1-18}$$

and that at any point in the tube the amplitude swings from its maximum to its minimum value in accordance with the relation $\cos(\omega t)$.

Other aspects of this solution will be examined in Appendix A. In particular, several forms of the pressure distribution along the tube will be obtained and a relation that yields the number of points in the tube at which "water curtains" can be formed will be deduced.

CHAPTER II

PREVIOUS RESEARCH

While the powder patterns formed in a resonant tube and used to measure sound velocity in the physics laboratory are of reasonably general knowledge, other phenomena in such a tube have reached a rather limited audience. As a matter of fact, a thorough understanding of many of the phenomena associated with the Kundt's tube has not been obtained, especially the Kundt's tube partially filled with a liquid. Because of this and to outline the historical development of the subject, the following discussion of a Kundt's tube is given along with the literature pertinent to the subject.

Kundt's Tube Containing Dust Particles

In 1866 Kundt(14,15) reported the appearance of some strange and striking patterns formed in a horizontal, closed tube containing air and a thin layer of powder of dust along the floor of the tube when the air was set into vibration. Kundt first produced these patterns by stroking the tube, but soon realized that in order to eliminate the effects of tube vibrations he would have to modify his equipment to vibrate the air with a rod located at one of the closed ends of the tube.

Kundt's original intent was to measure the velocity of sound in th resonant tube by the patterns the powder formed from standing waves in the tube. He accomplished his objective but he stumbled onto much mor in fact, he observed a part of a phenomenon that in many respects still puzzles investigators some one hundred years later. Not only was Kundt able to produce the pattern of velocity nodes and loops (minimum and maximum motion) as expected, he also found that the powder formed many interesting patterns on the floor of the tube depending, apparently, upon the amplitude and frequency of the vibrations.

One interesting example of the phenomena observed by Kundt concerns the behavior of the powder in the vicinity of the antinode or velocity loop of a standing wave. If the tube is resonated at a suitable frequency and power level, the powder begins to be arranged into curious patterns. Some of the dust in the tube forms extremely thin walls of particles directly on top of the dust that was originally distributed along the length of the tube.

One of the ironies of engineering and science enters at this point, for surely only a lack of the proper amplifier, signal generator and transducer kept Kundt from learning more of the behavior he had observed. If he had only had access to a source of sustained vibrations as did Andrade[11,12], Cook[16] and Pringle[17], he would have been able to observe that, if the vibrations were continued while the power level was increased even further changes in particle behavior occur. In fact, an increase in power level causes these walls to grow even higher, and, finally, a complete clearing of particles from between these walls except for the formation of smaller walls between each major wall (called minor walls) occurs. The powder at the velocity node remains motionless during these changes.

The walls nearest the antinode (velocity loop) are the largest, and these decrease in height toward the node. Any given wall is extremely thin and all of the investigators thus far mentioned as well as those referred to later report that these walls are only one particle thick.

With the walls in the condition described above, a sufficient increase in power level causes the walls to begin to transfer particles from wall to wall toward the nodes very rapidly until all of the powder forms in heaps at each side of the nodes. This is usually referred to as clearance.

One further observation with dust in a Kundt's tube should be pointed out. Both Cook and Pringle in 1930 independently reported that a thin disk of dust particles formed across the tube at the antinode when the power level was near, but slightly less than, that needed for clearance. The walls on each side of this disk remain unaffected and, like the walls, the disk was only one particle in thickness.

Kundt's Tube Containing Soap Films

Disks formed by soap films in a Kundt's tube have also been observed and employed to measure wave lengths by Mann and Stephens[18] and Robinson and Stephens[19].

The work of Robinson and Stephens "deals with the attempted use of these films to denote the position of nodes and antinodes in a Kundt's tube". These investigators first studied the behavior of stationary plane films in a tube closed at one end and vibrated by a loudspeaker at the other end. They were definitely able to establish regions of maximum and minimum vibrations at certain frequencies over a range of 300 to 3000 cycles per second. The scattering of reflected light from the film was employed to render the phenomenon visible. Their observations indicated "that the stationary film system responded most markedly to the following frequencies: 740, 840, 930, 1010, 1060 and 1240 cycles per second". (For a comparison, see the resonant frequencies given in Appendix B). These authors noticed an effect with stationary films that crops up in a somewhat different manner in this dissertation, namely, that the existence of a "blockage" in the tube (in the Robinson and Stephens case, a soap film, and the present work, a water curtain), affects the location of the normal vortex pattern in the Kundt's tube. Robinson and Stephens plotted the distance along the tube versus the natural numbers indicating the consecutive positions of the maximum disturbance. Their results and conclusions are best given by a direct quote:

> On plotting these distances against their respective numbers the same linear relation was found to hold for all frequencies, and the mean distance between consecutive maxima was calculated to be 7.6 cm. This result is contrary to what would be expected if the membranes were acting as true acoustic indicators of the positions of the nodes and antinodes of a "normal Kundt's tube". As an explanation it is suggested that the mode of vibration of the system is not determined solely by the acoustic vibration of the air, but also by the properties of the films and the interspaces. In this connexion it is not without significance that, below 740 and above 1240 cycles per second, the intensity of vibration diminished uniformly down the tube.

It should be emphasized that the nodes and antinodes (points of maximum and minimum motion) should shift position as the frequency changes.

Robinson and Stephens then virtually eliminated this blocking effect "by the use of a system of widely separated films moving slowly up the tube" in order that "each film in turn could pass through a position of node or antinode when the tube was in resonance." Under these conditions, "experiment showed that if the source of sound was sufficiently intense the positions of maximum vibration could be located with some degree of certainty by the pronounced vibration, or even bursting, of the film at these points." From preliminary experiments conducted in the resonant tube, the approximate position of the antinodes, or velocity loops, were determined. Then, when the film moved near one of these points, the sound was turned on and the position of maximum motion or bursting was noted. By repeating this procedure for several points along the tube, the wave length and hence the sound velocity could be determined.

Another point of some interest to this investigation was Robinson and Stephens' observations concerning the mode of vibration of the soap film. They found that "for small vibrations a definite system of radial and circular nodal lines makes itself clearly apparent on the surface of the film" (Waller[20,21,22,23] found a similar series of lines when vibrating various material on a horizontal plate or disk). In addition, Robinson and Stephens found that often a "miniature rainstorm" occurred in the space between a pair of films moving together up the tube. They state that "the effect was produced by a mutual bombardment with liquid particles ejected when the films passed through a region of maximum disturbance." This observation then leads naturally into the investigations of direct interest here.

Kundt's Tube Containing a Layer of Water

In 1874 and again in 1876 Dvorak[24,25] mentions experiments employing water in a resonant tube. These observations were a part of general studies he was conducting on sound waves in tubes. Dvorak noticed a motion of the water at the antinodes, but the sketch presented of the shape of the water surface is somewhat misleading. Again as in the case of Kundt, Dvorak employed a stroked rod to produce the vibrations in the tube and his results suffered as a result. Dvorak attributed the unusual surface behavior of the water to an excess mean pressure produced at the nodes by the second order effects in the air above the water.

In 1944 Howatson[26] published the first extensive investigation of the behavior of a layer of water in a Kundt's tube. His equipment was a decided improvement over that of Dvorak since a loudspeaker was employed as a source of vibrations. But even Howatson was limited in terms of modern equipment. His signal generator accuracy, power input to the tube and frequency measurement accuracy were limited, and equipment was not available with which to measure the sound pressure level in the tube. Nevertheless, Howatson was able to carry out an interesting observational study of liquid behavior in the tube. Many phenomena not previously observed by investigators of the Kundt's tube were found. In addition, Howatson attempted a quantitative evaluation of the pressure variation in the tube at resonance. The salient features of Howatson's work will be presented along with the results of his theoretical investigation.

It should be noted that several results of this study are at variance with the observations of Howatson; nevertheless Howatson's results are presented here with little comment. The points of difference will be discussed in later chapters as they arise.

Howatson points out that the antinodal spouts are remarkably sharp and localized. With "proper adjustment", it was reported that the spouts remain stable with their positions unaltered over long periods of time "except at the lowest frequencies when irregular fluctuations take place and multiple spouts are, in general, formed." These investigations, like those described here, cover the general range of frequencies from 300 to 1500 cycles per second. Howatson extended some observations to frequencies above 2000 cycles per second, but it was only noted that the intensity of sound produced was insufficient to initiate the spouts at these frequencies. Nevertheless, a pronounced curvature of the water surface at each of the higher resonant frequencies was observed.

The liquid most often used by Howatson and the liquid upon which most observations were based is acetone. The choice of acetone was based on the fact that it had "suitable physical properties, such as low viscosity, surface tension and density, and high refractive index for photographic purposes." A deficiency of power makes the use of such a liquid particularly desirable. In addition, Howatson employed methylated spirits, water, ether, petroleum oil and liquid paraffin.

With acetone as the liquid, Howatson found that the spouts formed so suddenly "that it cannot readily be followed by the eye." Occasionally a small ridge was seen on the surface transverse to the axis which increased in height very rapidly, especially near the walls of the tube, to completely fill the tube. Another perturbation that can assist in the formation of curtains was noted to be the presence of liquid drops thrown off by a neighboring spout previously formed at an adjacent antinode. With liquids such as acetone, Howatson states that "...the sheet is never complete, but breaks up on its upper half into small drops which are thrown upward and outward with considerable violence." At low frequencies, "...single, steady spouts do not form at any intensity."

Howatson's studies indicated that other liquids of low viscosity such as ether and water behaved substantially the same as acetone. For liquids of high viscosity such as petroleum oil or liquid paraffin, Howatson found that the curtains formed tended to seal the tube and lower the intensity on the side of the curtain remote from the speaker to an extent that he could not form further curtains.

Howatson solved Euler's equation for the mean pressure difference between each node and antinode based on the behavior of the air above the node. This difference was found to be given by

$$1/2\ \rho_o\ U_a^2\ , \tag{III-1}$$

where U_a is the maximum particle velocity at an antinode. A lack of equipment necessitated the estimation of the value of U_a by observing the motion of smoke particles above the liquid in the tube. These results were at variance with his observed pressure difference in the tube. (A further discussion of this is presented in Appendix A, where it is shown that the experimental value of U_a obtained by Howatson is probably incorrect.)

Howatson discussed the formation of the curtains and attributed their formation primarily to a "...rapid pressure gradient normal to the surface, the pressure gradient decreasing in the vertical direction...." as a result of a boundary layer built up on the liquid surface. However, Sanders[7] has pointed out that such an explanation is fundamentally incorrect from boundary layer considerations.

Howatson also reports some observations with liquid drops on the liquid surface. His studies indicated that the behavior of the drops were in keeping with the studies of Andrade[12] who used small spheres in a smoke-filled tube for his observations. Andrade's work will be discussed later in this chapter.

Hot Wire Studies in a Resonant Tube

A brief mention of another study somewhat related to the subject of this dissertation is in order at this point.

Fand and Kaye[27] employed another rather ingenious technique to locate the nodes and antinodes in a resonant sound field. These investigators passed a current through a wire located in an acoustic field with intense, stationary sound waves. By properly adjusting the current, the wire was made to yield a pattern of light and dark areas along its length. This was a result of maximum and minimum heat transfer at the points of maximum and minimum motion in the sound field.

General Circulations in a Kundt's Tube

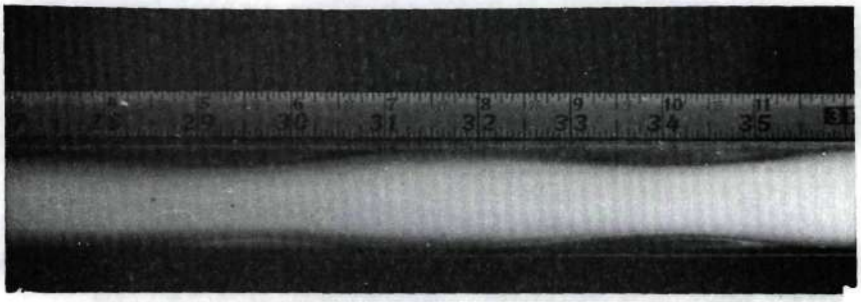
Explanations for the phenomena first noted by Kundt have been offered by various investigators. Rayleigh[2,3] was prompted to undertake a theoretical investigation of a resonant tube by some of the experimental observations of Dvorak[24,25]. These results were enlightening for it was found that the effects of viscosity predicted a secondary motion in the tubes in the form of vortices located between nodes and antinodes. However, Rayleigh did not pursue the particular phenomena in the Kundt's tube at any length.

Andrade[11,12] employed the vortex motion and general circulations predicted by Rayleigh to explain systematically the wall formation and clearance when dust was used in the Kundt's tube. Andrade not only made the vortex motion visible by the use of tobacco smoke as a tracing medium (see the photographs of Jackson and Johnson shown in Figure 3 and those of Purdy given in Figure 6) but he also found that other types of vortex motion were possible. For example, it was found that small spheres placed in the sound field had a vortex field attached to them when the intensity of the sound was sufficiently high. In fact, it was shown that this attached vortex field accounted for the attraction of particles under certain conditions and repulsion under others. Some of the conclusions reached by Andrade in two papers of 1931 are:

(a) "The movements of dust particles in the air in a sounding tube can be explained in terms of a general circulation of the air between node and antinode, and a vortex motion round every particle."

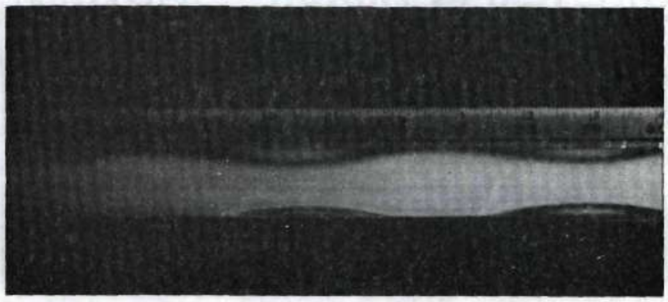
(b) "The vigor of the general circulation gains on that of the vortex motion as the sound vibrations increase in intensity, as a consequence of which the nature of the dust figures obtained is controlled largely by the intensity of the sound."

(c) "The forces between two particles in air, vibrating with an intensity such that they are surrounded by vortex systems of the type described, may be either attractive or repulsive, according to the



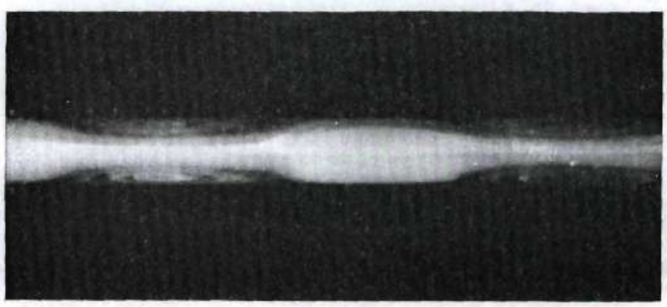
FLOW

(a) 1440 cps



FLOW

(b) 1600 cps



FLOW

(c) 1120 cps

Figure 6. Qualitative Smoke Patterns From Preliminary Investigations for Tube Flow.

distance of separation. For particles in the transverse position the force is one of attraction when the particles are within a distance of about a particle diameter, of repulsion at slightly greater distances. The longitudinal position is, at small distances, unstable, and particles tend both to set themselves transversely, and to come together. If the particles are constrained to be in a longitudinal position there is an equilibrium position when the vortex systems just touch, the forces being repulsive for less and attractive for slightly greater distances."

(d) "Owing to the lateral attraction and the longitudinal equilibrium position, ridges are formed, which are maintained by the vortex systems at fixed distances apart."

(e) "When the intensity is large, the general circulation carries the ridges towards the node in a manner described at length in the paper, the dust being deposited in a ridge to either side of the node. At very large intensity these ridges may coalesce to form one broad ridge at the node."

(f) "At certain intensities a sharp disc extending right across the tube and bounded by a marked ring, is formed at the antinode, the forces which maintain it being similar to those which maintain a ridge at the bottom of the tube, the reversed effect of gravity in the two cases explaining the instability which leads to the formation of one antinodal disc as contrasted with many ridges."

(g) "In a tube containing a gas set in vibration by a diaphragm there is a circulation, the gas moving from antinode to node along the wall, and returning up the center, as predicted by Lord Rayleigh."

(h) "Any particle which does not share the vibratory motion of the air may be the center of a vortex motion, which is symmetrical about both a longitudinal and a transverse plane through the particle if the amplitude of vibration is uniform in the neighborhood of the particle, but about a longitudinal plane only if the amplitude has a marked gradient.... "

(i) "It is shown that in all previous experiments on the forces between spheres in vibrating air the motion, which has been tacitly assumed by the workers to be irrotational, was actually vortex motion."

It should be pointed out that even though these explanations deal with the motion of air in a tube containing a layer of powder, the motion shown to exist influences the motion of the liquid in a tube partially filled with a liquid instead of a powder. In fact, Howatson employed Andrade's arguments in discussing the behavior of liquid drops on the surface of a liquid. However, high intensity, non-isothermal conditions within the tube alter the motion as will be discussed in the next section.

Rayleigh's assumption of isothermal behavior inside the tube was incorrect even for low intensities; but, fortunately, Rayleigh's results did correctly predict the circulations used and demonstrated by Andrade to explain the behavior of dust particles. Westervelt[4] in 1953 corrected Rayleigh's isothermal assumption to isentropic, but erred in discarding some of the terms. The general case of secondary flow including through-flow (this makes Rayleigh's and Westervelt's solutions a special case of zero through-flow velocity) was presented in 1963 by Purdy[5] and Purdy, et al.[6] (see the photographs and sketch given by Purdy and shown in Figures 6 and 7).

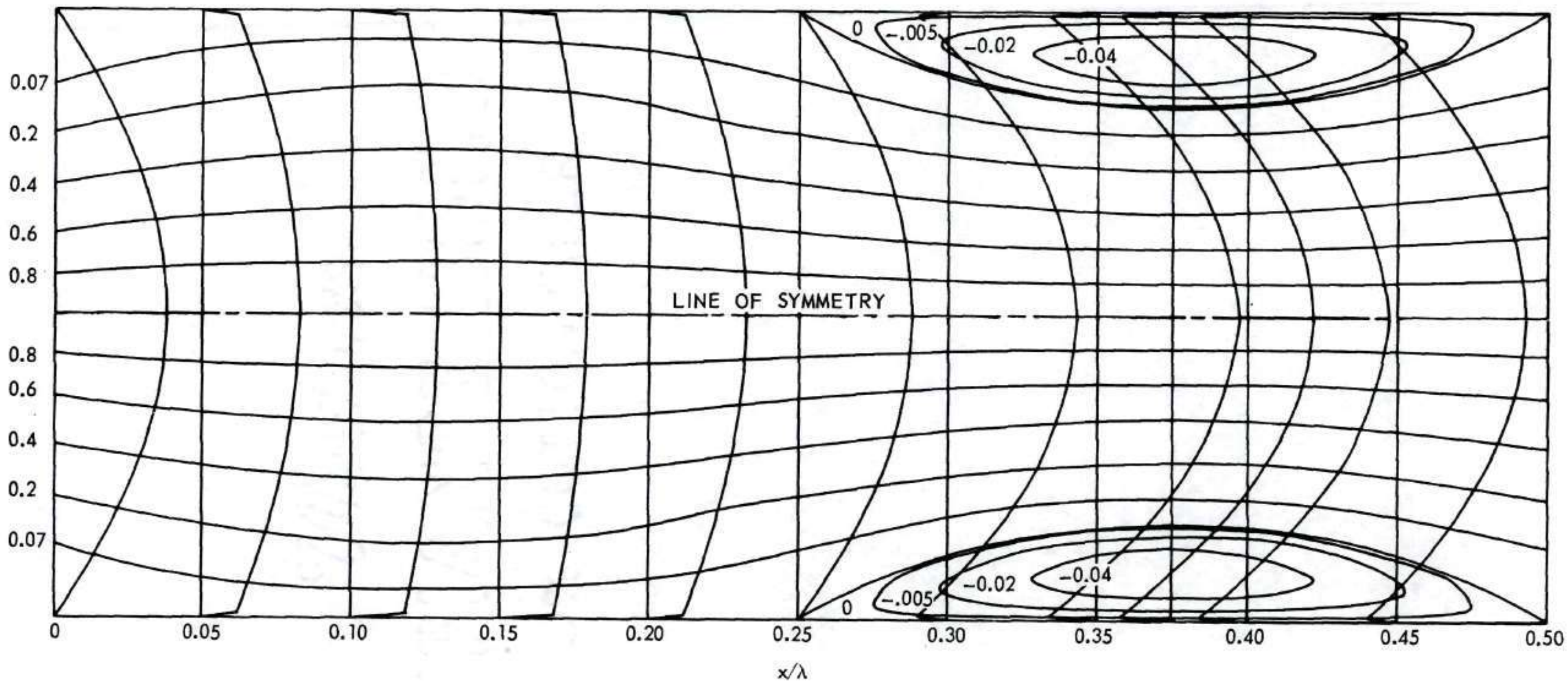


Figure 7. Graphical Representation of Streamlines With Secondary Flow.

Non-Isothermal Circulations

Andrade mentioned in passing that convection currents apparently distorted the circulation patterns set up in a resonant tube. He surrounded some of his tubes with water jackets to avoid these convection currents. However, it was not until 1960 that the effects of convection received further attention in a study by Jackson and Johnson[13]. The photographic results of these investigators repeated in Figures 8 and 9 show quite clearly that the entire flow pattern in the tube can be changed under certain conditions. The latex diaphragm noted in Figure 8 was used over the driver in an unsuccessful attempt to eliminate streaming. Jackson and Johnson postulated that the resulting change in the vortex patterns was a result of natural convection currents at the velocity antinodes. They showed that the violent motion at the antinodes for high intensities could cause a rise in the local temperature as a result of local viscous dissipation. This results in a convection current rising at the antinode. Though Jackson and Johnson did not point it out, such a current would result in a reversal of the direction of the velocity over the lower surface of the tube.* In addition, some of the cells formed and photographed by these authors completely fill the crossection of the tube, whereas the cells predicted by Rayleigh and observed by Andrade form matched vortex pairs on each side of the centerline of the tube. These two types of circulation are shown schematically in Figures 4 and 9. Cells containing water curtains are shown developing in Figure 10.

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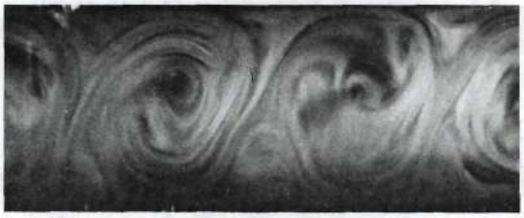
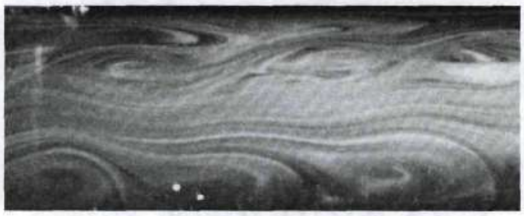
* Actually, a study of the sketch on page 18 of Jackson and Johnson's report will lead to this conclusion.

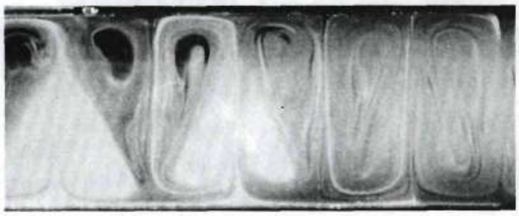


a. 5 WATTS
WITH LATEX DIAPHRAGM

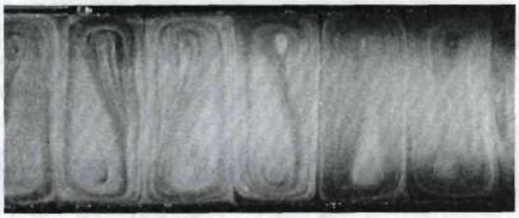


b. 25 WATTS
WITH LATEX DIAPHRAGM

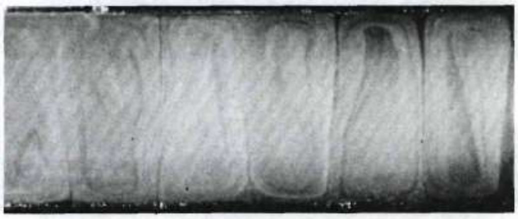
c. 50 WATTS
WITH LATEX DIAPHRAGM



d. 5 WATTS



e. 25 WATTS



f. 50 WATTS

Figure 8. Jackson and Johnson's Non-Isothermal Vortices.

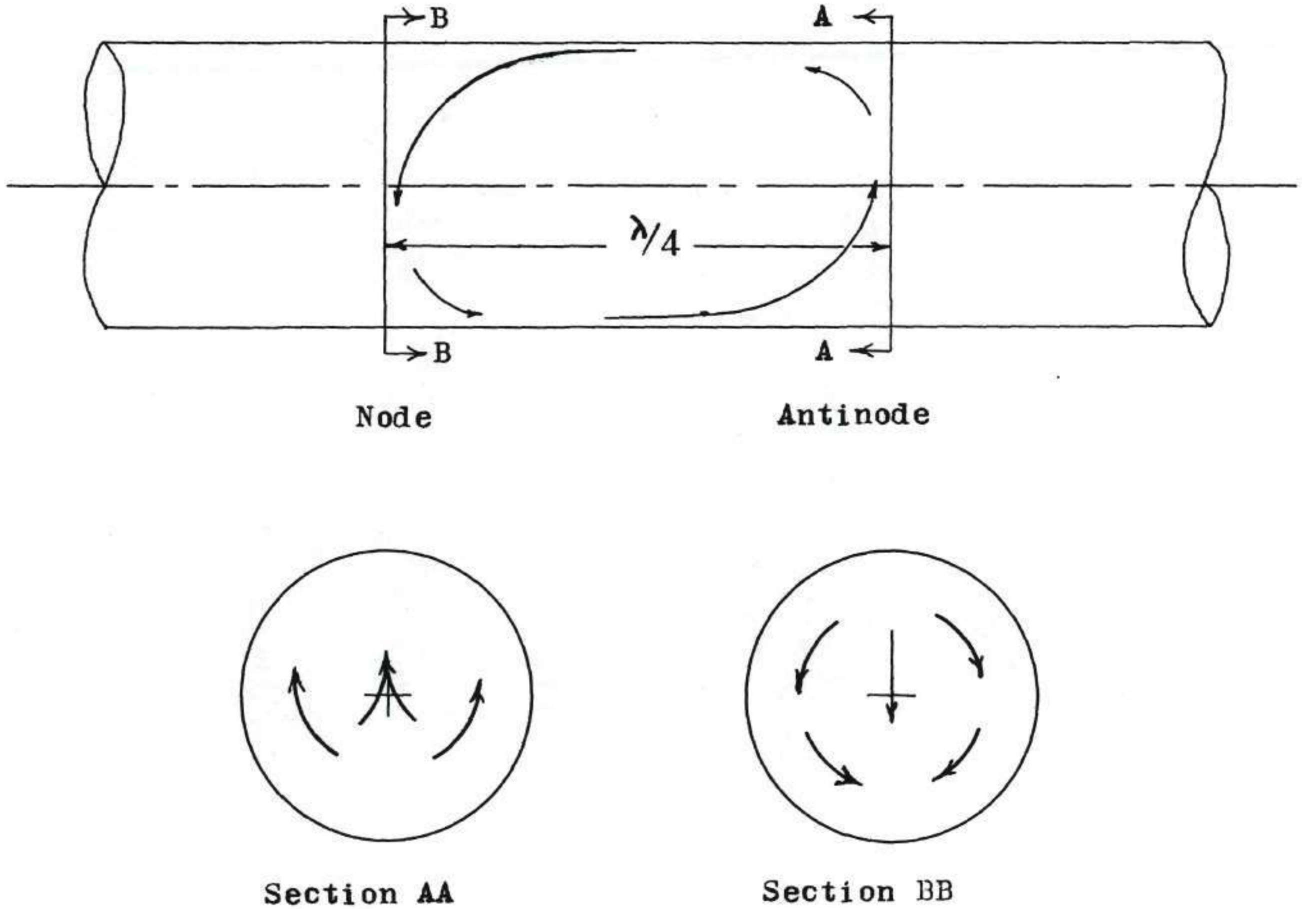


Figure 9. Sketch of Circulations in Non-Isothermal Cells.

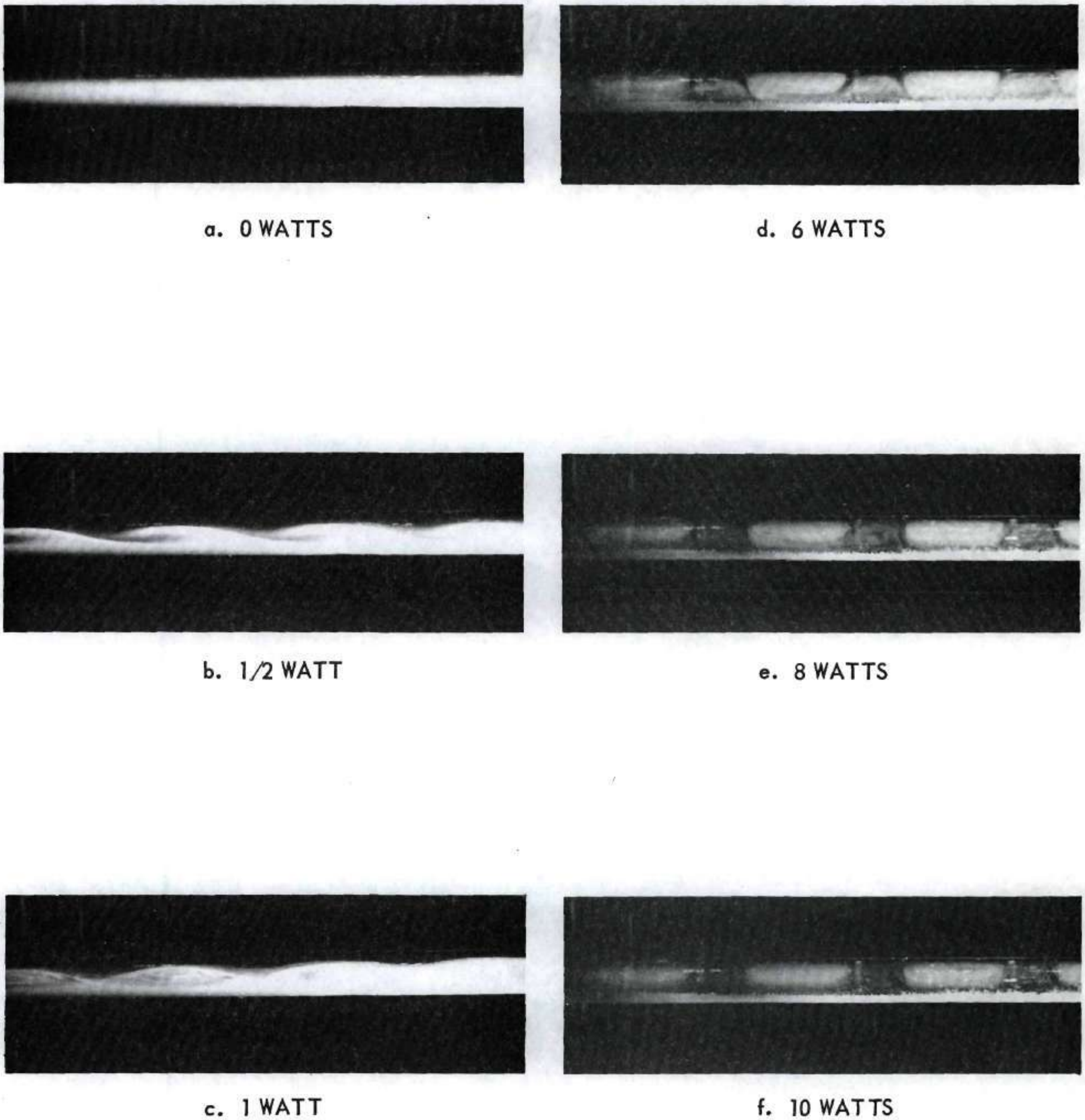


Figure 10. Cells Developing in a Circular Tube with Water Curtains as Observed by Jackson and Johnson[13].

Further discussion of this fundamental difference in circulation patterns will be found in Chapter IV where the behavior is used to propose an explanation for the observed difference in the directions of flow of dust and water in a Kundt's tube. In addition, it is proposed in Chapter IV that the type of circulation observed by Jackson and Johnson does not result from convection currents alone. Instead, it is proposed that these large vortices result primarily from the excitation of higher modes of vibration. This explanation is then employed in a proposed physical explanation of the formation of liquid curtains.

CHAPTER III

QUALITATIVE STUDIES

In this chapter the general behavior of a layer of liquid in a Kundt's tube will first be given. This general behavior has, of course, been reported by previous investigators as discussed in Chapter II.

A major part of this chapter will be devoted to qualitative descriptions of interesting, and sometimes striking, phenomena obtained in the Kundt's tube and not previously reported in the literature. In some cases these observations differ from those reported before. This discussion will deal primarily with a tube containing water or acetone.

An attempt to employ the Kundt's tube to desalinate sea water will be described in the closing portion of this chapter.

General Behavior

A liquid was placed in a horizontal glass tube. The tube was closed at one end except for a small opening which was then sealed by the sound pressure level (SPL) pickup. The other end had a dam across the lower portion of the tube sufficient to contain the liquid. With the horn protruding slightly into the tube, the power and frequency were adjusted to produce the desired phenomena (see Chapter V for a detailed description of the experimental procedure).

With the frequency adjusted to resonance the power was slowly raised to higher levels of input. At first there is no discernible effect within the tube. In general the first noticeable effect occurs quite abruptly even though the power level is being increased in small increments. This first manifestation of the resonant phenomenon is a slight, stationary, sinuous shape of the liquid surface. As the power input to the tube is increased, the surface curvature becomes more pronounced. The surface assumes a shape that appears to be a perfect sine wave of low amplitude. For the range of frequencies of stable operation there is no discernible movement of the liquid (see Figure 11).

Further small increases in power input have no apparent effect until, suddenly, upon reaching a critical intensity, a thin sheet or curtain of liquid jumps across the tube from one of the crests of a standing liquid wave and remains as long as the power is continued to the driver. The action of this curtain of liquid is rather violent for in small tubes, under two inches in diameter, it strikes the upper wall of the tube with some force and in larger tubes carries for a distance of two or more inches. A further increase in the power input will either produce another curtain at the same crest or at another crest in the tube (see Figures 12 and 13).

The crests and troughs of the sinuous surface correspond to the velocity antinodes and nodes, respectively, as can be observed from the fact that the closed end of the tube corresponds to a trough. An antinode is usually at or near the open end of the tube.

For stable operation, the spouts remain at the top of the crests and are located one-half wave length apart. Thus, these spouts can be used to determine the sound velocity when used in conjunction with the frequency.

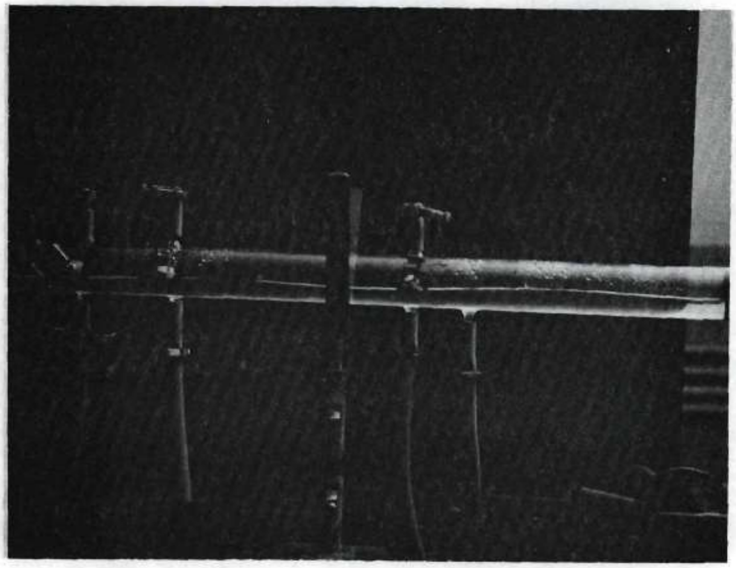


Figure 11. Sinuous Shape of Liquid Surface in a Resonant Tube.

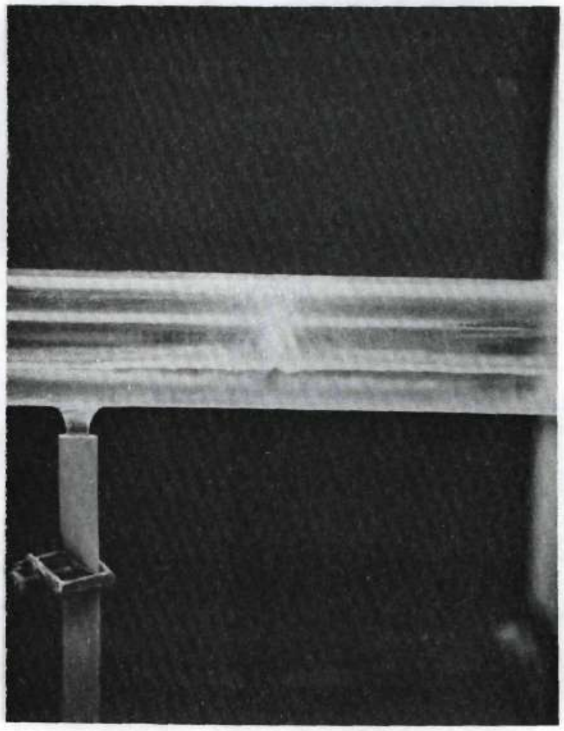


Figure 12. Crest with a Single Liquid Curtain.

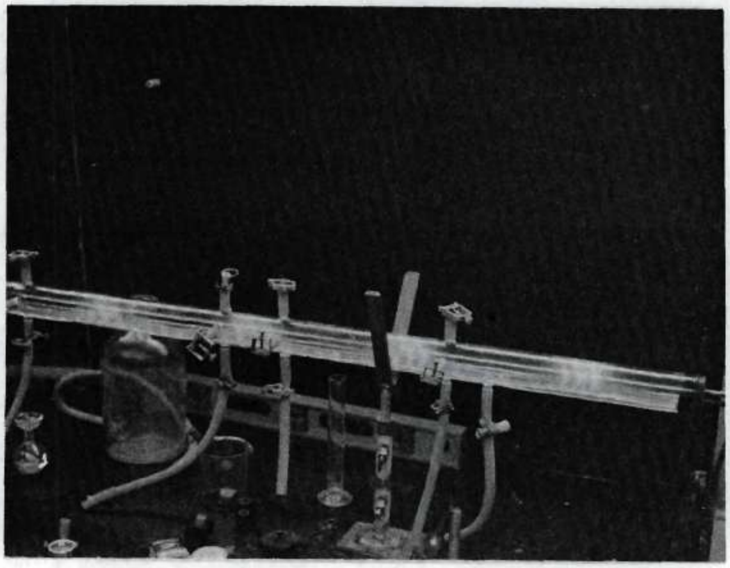


Figure 13. Curtains Located at More Than One Crest.

Under certain conditions, the behavior in the tube becomes unstable. This instability is usually characterized by moving surface waves and the continuous collapse and rise of one or more curtains at the antinodes.

Even though the inception of a curtain is generally too rapid to follow with the eye, Howatson pointed out that an occasional warning is afforded by small surface ripples that travel toward the top of a crest where they burst into a curtain.

A means of quantitatively determining the conditions in the tube necessary to produce a curtain is presented in Chapter IV along with several other aspects of curtain behavior.

Qualitative Observations Related to Curtain Formation

Howatson mentioned the difficulty of forming curtains when his tube contained water instead of acetone. That this was a result of power input limitations and not a characteristic of water is demonstrated by the fact that with the equipment employed in this research curtains could be obtained over the entire range of frequencies investigated by Howatson. An examination of the SPL data in Table 3 indicates that 6 db. to 10 db. greater SPL in the tube is needed to form water curtains than is needed to form acetone curtains at the same frequency in the same tube. This, of course, represents a 400 to 1,000 per cent increase in power input. Howatson recognized the power limitation and thus limited his studies to small tubes. The major portion of Howatson's observations were for liquids of low surface tension and viscosity. Perhaps, the most striking illustration of the effect of surface tension on curtain formation is afforded by the example in the next paragraph.

With the tube in a resonant condition and the power level such that the sinuous shape of the surface was present (but well below the power level ordinarily required for curtain formation) a few drops of ethylene glycol were added to the water near a crest. Quicker than the eye could follow, this crest exploded into multiple curtains and flung the solution containing ethylene glycol to adjacent crests. These, in turn, exploded into multiple curtains. In rapid succession this effect followed from crest to crest and the tube became filled with films of foaming solution rather than true curtains. The films thus formed blocked the tube and no effects of resonance could be discerned outside the immediate neighborhood of the driver (approximately one-half wave length). When the sound was turned off most of these films remained in place though many of them would coalesce. This tendency to coalesce indicates that even though the effects of the acoustic vibrations at points removed from the horn were not discernible to the eye when the tube was blocked by these films, enough of an effect was present to keep most of the films separated until the intensity was reduced to zero. After a means of measuring the SPL at the closed end of the tube was obtained, the effect of blocking became somewhat more quantitative. For, when a curtain was formed in the tube, the SPL at the closed end of the tube was observed to drop one or more decibels depending upon whether or not the curtain was a solid sheet (as in a small tube with water, or any tube with ethylene glycol added) or broke up into drops and only partially blocked the tube (as in the larger tubes containing water). The greatest reduction in SPL corresponded to the most blockage.

When the first observations of the behavior of the water curtains were made, the equipment for determining SPL inside the tube was not available. This led to interesting results concerning curtain behavior as a function of the power input instead of the tube SPL that might have gone unnoticed had the proper equipment been available. It was found that if a frequency was fixed such that the tube had N_p possible points for curtain formation, i.e. N_p crests, then, when N/N_p, where N is the number of curtains actually formed at a given power input, was plotted as a function of power input to the driver, it yielded a straight line on rectangular coordinates. However, there was a different line for each frequency and water level. Later, when equipment for the measurement of SPL inside the tube became available, it was found that the water depth played little or no part in the correlation. This preliminary correlation is presented in Chapter IV where the power input necessary to form curtains is clearly seen to be a function of the water depth and frequency. The final correlation of curtain "threshold" in terms of SPL shows no such depend ncy upon water level since it is based on actual conditions inside the tube instead of the power input to the speaker horn (these correlations are discussed in detail in Chapter IV). This, then, indicates that the energy input necessary to obtain a given SPL in the tube is a function of water depth and that the curtain behavior in the tube is a function only of the actual SPL in the tube and is independent of the water depth. This is an important point, for it indicates that even though the SPL in the tube must be a given value for a particular phenomena to occur, the use of smaller tubes allows the use of equipment with lower ratings of input power for demonstrations and also for research in limited ranges. It should be emphasized, however, that not all the phenomena are manifested in the smaller tube. For, as has been pointed out, the curtains form a solid sheet and tend to block a small tube, whereas the curtains break up before reaching the top of larger tubes and only partially block them.

Another interesting observation is that the power input necessary to obtain two curtains at one crest is approximately the same as the power input necessary to obtain one curtain each for two crests. This appears to hold true for any number of curtains or crests. In fact, a plot of N/N_p as a function of power input for water continues to be approximately a straight line as N/N_p increases beyond unity. The instability resulting when all crests have curtains and some crests have multiple curtains cast doubt on any results obtained under these conditions. Nevertheless, values obtained with care give an excellent indication of this behavior especially since stability with more curtains than crests is occasionally possible.

Howatson found that "Though multiple spouts formed at a single antinode are generally short-lived, it is occasionally possible to excite near a single antinode two spouts which remain stable for some time at a fixed distance apart. This occurrence appears to be associated with irregularities in the motion, as the note emitted by the speaker is noticeably inpure when double spouts are formed." The results of the present investigation do not agree with these contentions. First, it was found that for frequencies less than about 1,000 cps stable, multiple spouts could be formed with little difficulty in water and even less difficulty in acetone (see the photographs of Figures 14 and 15). In fact,

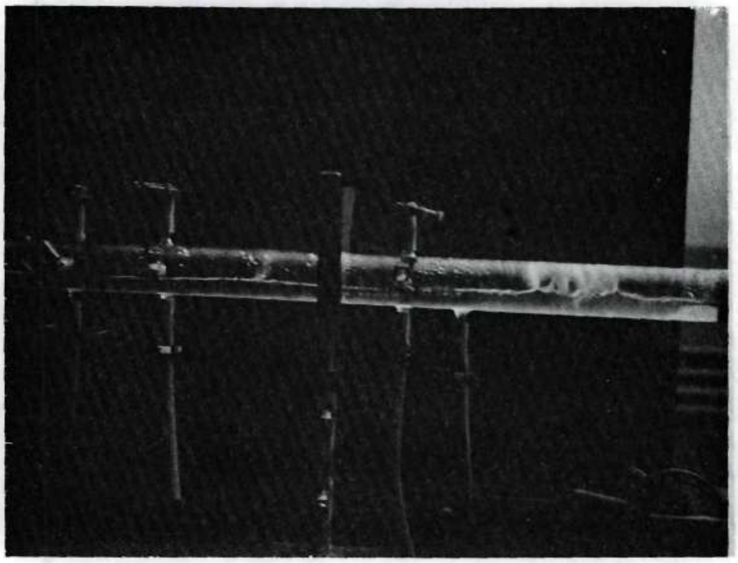


Figure 14. Multiple Curtains in Water.

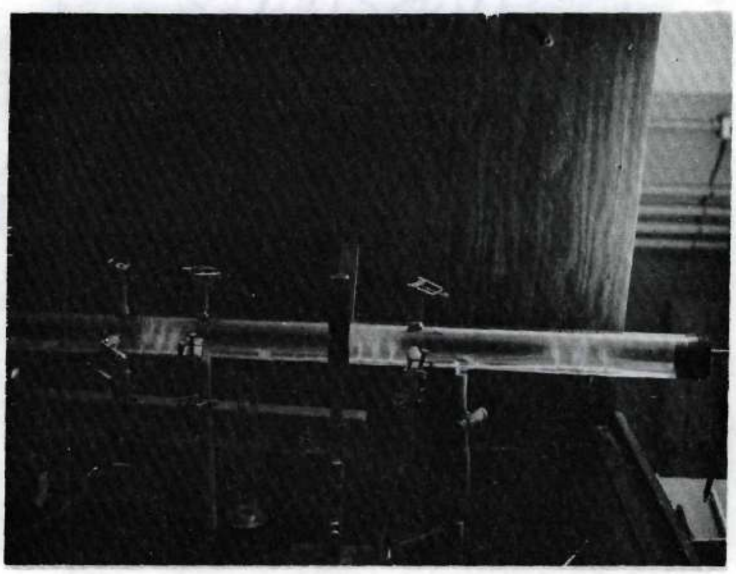


Figure 15. Multiple Curtains in Acetone.

it was found that in most cases the first two stable spouts formed at the same crest, then spouts formed at the remaining crests as the power was increased. These multiple spouts in this range were not short-lived. Next, the note emitted by the driver was not found to be impure when multiple spouts were formed or even when unstable multiple spouts were formed. Both the signal of the sine wave generator put into the driver and the SPL output signal were monitored on a dual-input oscilloscope (see, for example, Figures 48 and 49). These furnish the necessary evidence as to what actually happens as opposed to what the ear apparently detects. When the SPL probe is placed at the horn exit during unstable operation, the horn output wave follows the signal generator input wave with a shift in phase but little or no change in shape. But, when the SPL microphone is placed either on the side of the unstable curtains removed from the horn or near the curtains, the output from the probe is distorted. Actually, this shouldn't be too surprising because the moving curtains, which partially block the tube, change the note discernible to the ear as they move. However, the input to the tube was held constant. Thus, it is doubtful that the impurity of the signal serves to explain the formation of multiple curtains as Howatson suggests.

Multiple spout formation at a given crest is much more likely explained by the fact that once a spout is formed the water striking the surface causes disturbances in the form of small waves and floating drops which have small vortex formations attached to them. The vortices attached to the waves or ripples probably generate a second, third, or forth (or more, as the case may be) curtain. But only if the power is sufficiently high to create the next curtain does the newly generated curtain persist. If the power is near, but not quite sufficient, to generate a stable curtain, a curtain often forms from these ripples and then collapses and then the entire process begins all over again. In any case, the vortices observed by Andrade do attach themselves to the drops striking the surface.

There is a definite difference between the SPL in the tube necessary to cause a curtain to form and the SPL necessary to sustain a curtain once it has formed. When the SPL has been raised to the point where a curtain just breaks and the spouting action begins, it can then be reduced by several db. with no apparent effect on the curtain. This is probably a result of breaking the surface tension and the fact that viscous drag forces on the curtain help to sustain its motion (see Chapter IV).

Another aspect of the effect of SPL on curtains that has apparently gone unnoticed results from a very careful lowering of the SPL in the tube when a curtain stands in the tube. If sufficient care is taken, a curtain can be made to become weak and extend only partially across the tube. Occasionally this weak curtain can be made to remain stable, but more often this condition persists for thirty seconds to three or four minutes and then suddenly collapses. On many occasions this collapse is immediately followed by a feeble attempt to form another partial curtain probably as a result of the waves formed when the curtain collapsed.

In connection with this last point, it should be pointed out that sloshing, or traveling, waves superimposed on the stationary waves and due to off-resonance conditions or other surface disturbances tended to form temporary curtains at SPL's below the values necessary for stable curtains. This most often occurs at frequencies greater than about 900 cps. In fact, stable curtains were seldom formed at frequencies exceeding 1200 cps in any of the tubes employed in the experiments. At the higher frequencies there appeared to be a coupling of the driver, the air column and the water that resulted in traveling waves instead of standing waves. The curtains formed from the sloshing never persisted for any length of time except in those cases where the SPL far exceeded that necessary to form stable curtains. The usual behavior during instability was the formation of a curtain as the crests on the water surface reached a peak height and the immediate collapse as the crest dropped, only to reform as the crest rose again to its peak height. Under these conditions, short-lived curtains usually appeared at more than one of the crests; multiple curtains at a given crest were never observed when this sloshing was taking place however. It would appear that the momentum of the rising wave breaks the surface tension and allows the curtain to form at a lowered SPL; then the falling crest once again allows the surface tension forces to predominate and causes the curtain to collapse.

Howatson states that

> At higher frequencies a general unsteadiness and tendency for multiple spout formation is also evident when the intensity is very high, but, as already mentioned, on lowering the intensity or altering the frequency slightly the spouts become perfectly steady. At low frequencies, however, single, steady spouts do not form at any intensity.

This was not true in the case of these investigations, for considerable difficulty was encountered in forming steady curtains at higher frequencies regardless of the care taken. However, no difficulty was encountered in forming single, steady curtains at lower frequencies.* One possible explanation of Howatson's difficulty in forming steady curtains at low frequency is that he did not have available the power to form curtains at these frequencies. An examination of Chapter IV and Appendix B will show that the power input necessary to form stable curtains rises very rapidly as the frequency is lowered. In some cases the power available for the present investigations (240 watts input) was not sufficient to break the surface at the lowest resonant frequencies. It can thus be speculated that Howatson formed these unsteady curtains at non-resonant frequencies and that the behavior previously described for non-resonant conditions then ensued.

Other surface distrubances cause the curtains to form at SPL's less than those for normal operation. Quite often a curtain forms around the horn if it extends into the tube and over the water. When small rods or other objects are placed into the tube, either on or near the water surface, curtains form at points on or near the tip of the rod. This might at first be thought to be a result of the rod's vibration assisting in breaking the surface tension, but it should be emphasized that it was not necessary for the rod or horn actually to touch the water's surface to cause curtains to form at low power levels or off-resonance conditions. An examination of Andrade's work[11,12] in a smoke-filled tube

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* It should be noted that Howatson might mean by high frequencies that these were frequencies in the range of 500 to 1,000 cps, in which case the results of these investigations agree with his; but, if he means frequencies in the range of 1,200 to 3,000 cps, these investigations show only a few cases of reasonably stable formation.

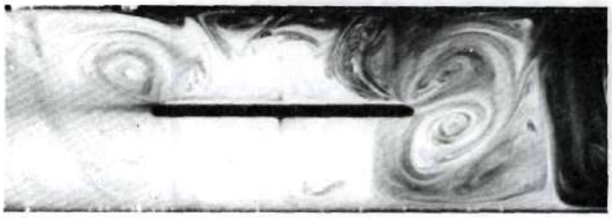
yields what must certainly be the explanation. As previously discussed in Chapter II, when small spheres, rods, or plates are placed in an acoustic field, vortices form about these objects as shown by the photographs of Figure 16. These vortices then evidently promote the formation of curtains. In fact, only at high power levels do the curtains thus formed extend across the entire area of the tube; instead, the curtains usually extend only between the water surface and some point on the rod. In the case of the horn protruding into the tube, the curtain usually surrounded the horn and filled the tube when a curtain formed beneath the horn.

Qualitative Observations Related to Curtain Behavior

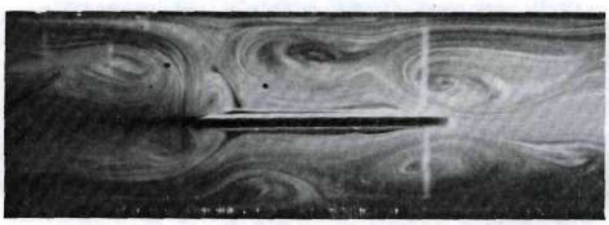
The physical condition of the curtains varied with tube size and with the physical properties of the liquid in the tube, i.e., with frequency, power input, etc. The following is a discussion of the various physical observations related to curtain behavior.

When a liquid that did not form persistent films across the tube even when the power was switched off, as did, for example, the ethylene glycol-water or soap-water mixtures, was resonated in the small tubes (1-1/8 inches I.D.) at power levels sufficient to form curtains, these curtains appear to form a continuous sheet whose thickness varied from 1/5 to 1/10 inch at the base to a minimum of approximately 1/32 inch at a point near the top of the tube.

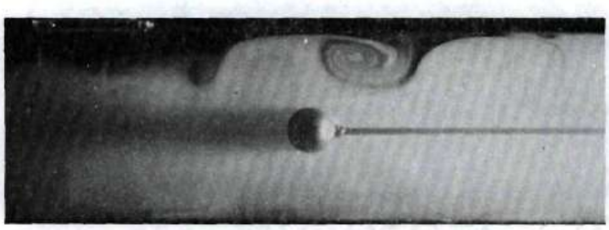
For the larger tubes (1-3/4 and 2-3/4 inches I.D.) the physical appearance of the curtains was somewhat different. The curtain did not form a sheet of liquid that was continuous over the tube's crossection.



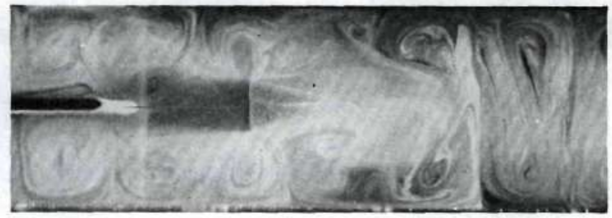
a. 4 WATTS



b. 30 WATTS
WITH LATEX DIAPHRAGM

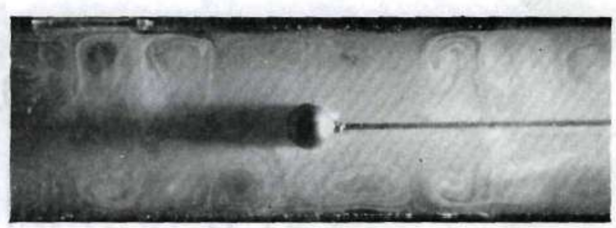


c. 4 WATTS



d. 4 WATTS

e. 7 WATTS



f. 20 WATTS

Figure 16. Vortices Formed About Objects in Acoustic Fields.

The curtain was usually continuous across a portion of the free area, (ranging from 1/3 to 2/3 of the vertical distance). It then broke up into discrete streams of drops which continued to the top of the tube, or, in some cases, continued in a parabolic path along the longitudinal axis of the tube to a maximum height near, but not completely to, the top of the tube and falling back to the liquid surface. In addition, large voids usually formed near the tube walls in the larger tubes. Thus, the liquid did not generally touch the tube between the surface and the top of the tube. Sketches of the appearance of these curtains as viewed along the longitudinal axis of the tube and as viewed perpendicular to this axis are shown in Figures 17 and 18. In addition the close-up photograph of Figure 19 showing a water curtain in the 1-3/4 inch tube indicates the appearance of curtains. The photograph of Figure 20 showing multiple curtains of acetone indicates the tendency of acetone to form a fine spray instead of discrete, large drops as did water.

The curtains in the photographs are all very nearly vertical. This was not always the case. Curtains standing vertically in the tube can be made to lean either toward the horn or away from it by adjusting the frequency to values slightly below or above the resonant frequency. If the frequency is more than 5 to 20 cps from resonance, the curtains collapse and the surface becomes level once again. In addition, the curtains can be made to tilt away from the horn by raising the SPL in the tube to levels well in excess of that needed to form stable curtains at the crests. In both of these cases the tilting can be explained by the general circulations along the longitudinal axis of the tube first made visible by the

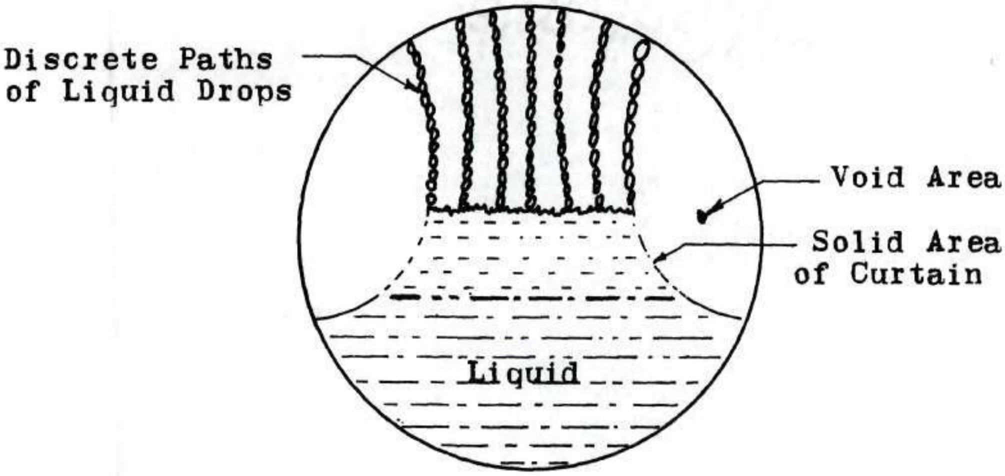


Figure 17. Crossectional View of Liquid Curtains in Large Tubes.

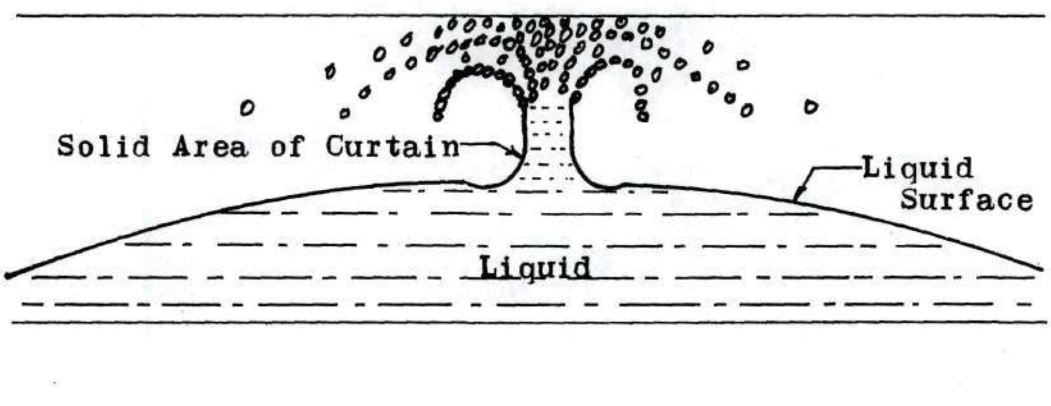


Figure 18. Side View of Liquid Curtains in Large Tubes.

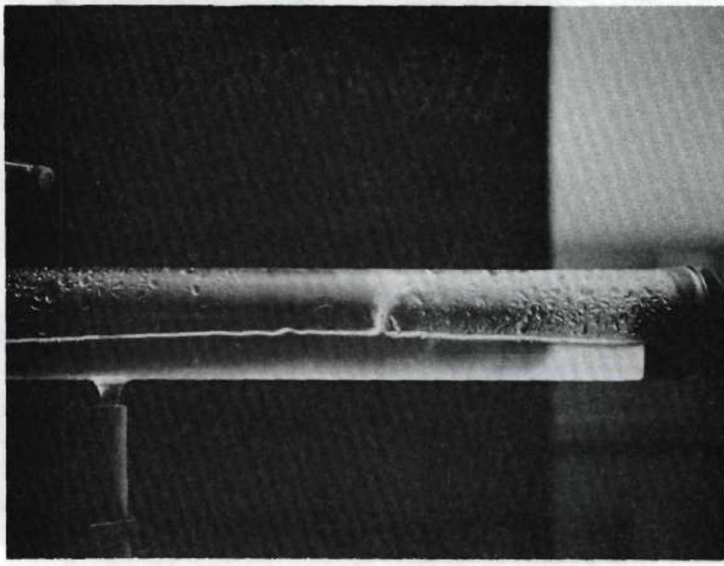


Figure 19. Close-Up View of a Water Curtain.

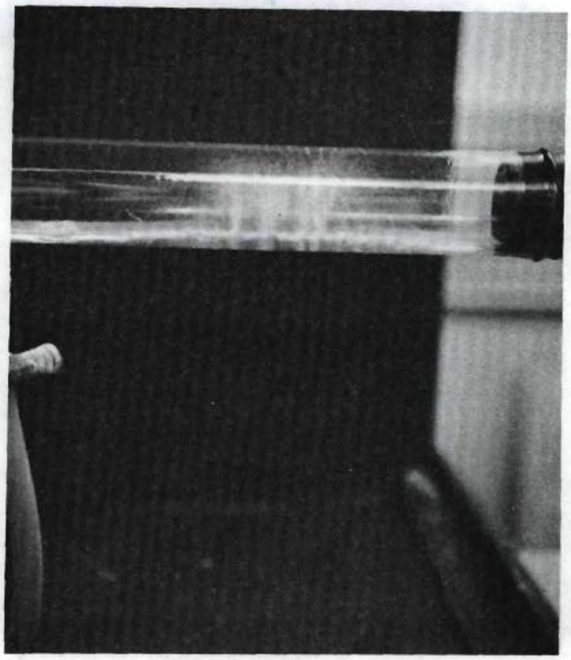


Figure 20. Multiple Curtains of Acetone Showing Fine Spray.

smoke in Andrade's tubes. In both cases, the curtains usually become unstable when these two variables are adjusted to extreme conditions. In fact, at very high power levels, the water is often driven toward the closed end of the tube when the curtains are tilted.

Howatson stated that, "With liquids such as acetone the sheet [curtain] is never complete, but breaks up on its upper half into small drops which are thrown upward and outward with considerable violence." This statement is at variance with the observations of this research. For in the small tube, both water and acetone appeared to fill completely the crossection under conditions of sufficiently high intensity in the tube.

At a later point in his paper Howatson stated "With water on the other hand, owing to its relatively high surface tension, the antinodal spouts are difficult to excite; nor do they break up readily into drops, taking the form rather of thin sheets of liquid. These films or sheets, extending as they do across practically the whole crossection, reduce considerably the intensity of vibration on the side remote from the speaker, so that it is difficult to maintain more than two or three spout in action simultaneously." The present study shows that the water definitely does break up into drops as has been noted in the case of the larger tubes and as is clearly shown in the photograph of Figure 21. The larger the tube, the more readily the water forms drops. Also, the inability of Howatson to form "more than two or three spouts" was the result of his power limitations, for, on many occasions during the present study multiple curtains were formed on each of two to ten crests (depending on the frequency) as interesting demonstrations to visitors.

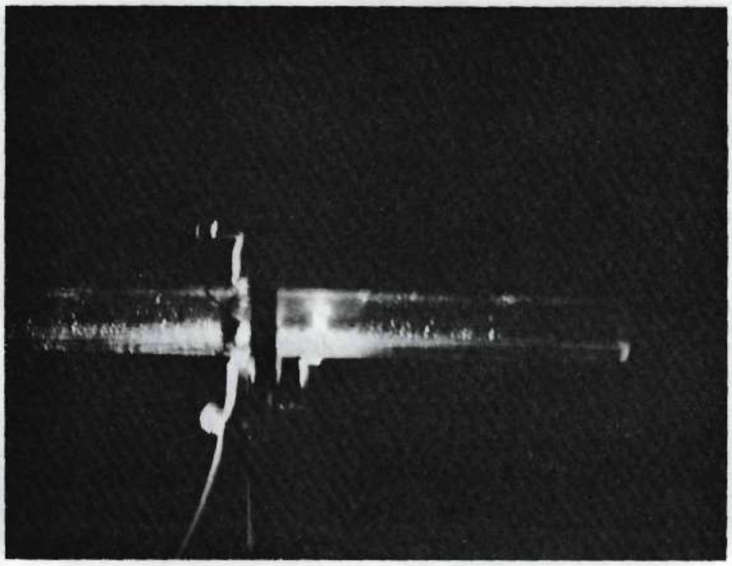


Figure 21. Drops Generated by the Action of a Water Curtain.

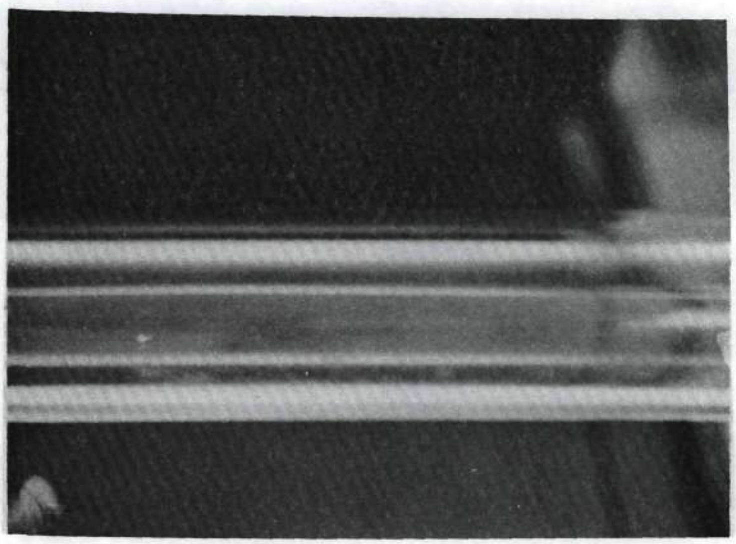


Figure 22. Single Drop of Acetone on Liquid Surface Viewed Nearly Parallel to the Surface.

Observations of Drop Behavior on the Liquid Surface

Drops formed as the curtain breaks up near the top of the tube or as it strikes the top of the tube often remain on the surface of the liquid instead of coalescing with the main body of the liquid when they fall back to the surface. Even though Howatson only obtained this effect "to any extent" with methylated sprits (alcohol) and melted paraffin, this effect was obtained at will in this research with water and acetone as well as with methyl alcohol. Figure 21 shows the general appearance of these drops as they are generated by water curtains. Figures 22 and 23 are photographs of a single drop of acetone spinning on the acetone surface as viewed at two different angles relative to the liquid surface. The view of Figure 22 is very nearly parallel to the surface of the liquid and the drop has the appearance of a small pearl sitting on the surface of the liquid. The view of Figure 23 is at an angle of approximately 45 degrees to the acetone surface. Here, the drop appears to have "butterfly wings" due to light reflections.

These photographs illustrate, among other things,an observation that does not appear to have been made before. That is, these drops appear to be spinning and not merely floating on the liquid surface. That this is true was first evident from watching a small piece of trash trapped in one of the drops. This is further borne out by the fact that the drops are blurred to some extent in all of the photographs. The shutter speed of the camera was sufficient to stop the motion of the drops in the air or in their paths over the surface of the liquid, but, the drops still appear blurred in all of the photographs taken on the liquid surface as shown in Figure 24, for example.

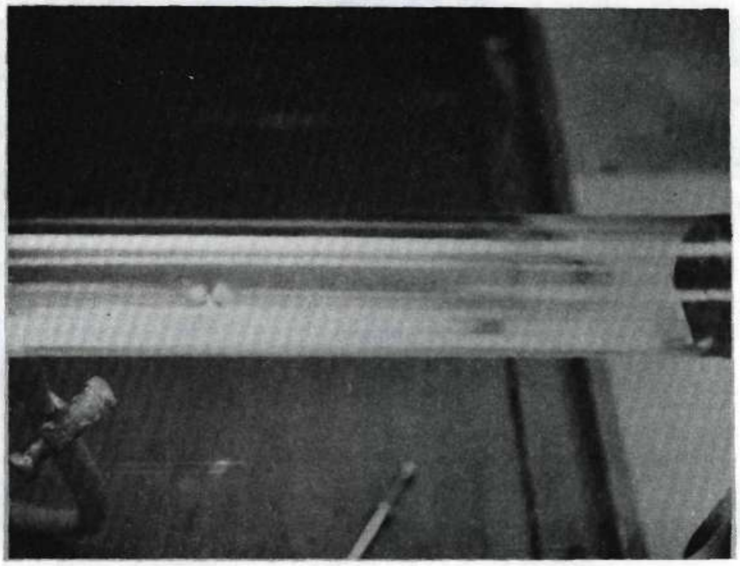


Figure 23. Single Drop of Acetone on Liquid Surface Viewed at 45° to the Surface.

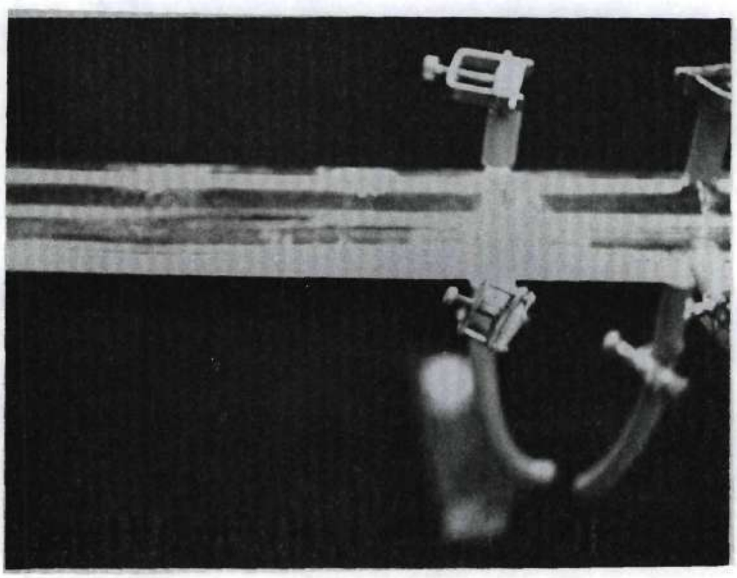


Figure 24. Water Drops Indicating Blurring Motion.

The "butterfly wings" apparently attached to the drop of Figure 23 are the result of light reflected from surface indentations near the floating drop. Since these appear to be separate indentations and not a uniform depression around the drop, it seems reasonable to assume that they are caused by the vortices that are expected to be attached to the drop in an acoustic field (based on the research of Andrade[25] discussed in Chapter II).

One or more drops can be made to float on the surface of the liquid with no curtains present as follows: First, the power is raised to a level that forms curtains and thus drops; then the power is slowly reduced to the point where the curtains collapse. Usually the surface of the liquid is covered with drops at this point if care was taken in reducing the power. If it is desired to maintain a large number of drops in action, the power is immediately increased to a point near, but below, that required for a curtain to form again. The presence of the drops will cause a curtain to form at a tube SPL below that normally required, and thus care must be taken not to raise the power level to this point; this requires practice and patience. If only one drop is desired, the power is lowered even further below that at which the curtain collapsed and is held at this level until all but one of the drops has coalesced with the liquid; then, very quickly, the power level is raised almost to that required to form curtains. In either case, it is necessary to maintain the power near the level required to form curtains if the drops are to persist for any length of time. These drops persist from a few seconds to twenty or more minutes depending upon the experimenter's skill in maintaining the proper power input and, apparently, on the type of collision the drop has with the wall in its random path on the surface. The drops thus formed are a source of continuous fascination as a result of their many modes of motion and behavior.

Howatson, in discussing the behavior of drops, stated that "...they invariably tend to arrange themselves in parallel rows transverse to the axis of the tube on each side of the antinodal spout." Though this is definitely one of the patterns observed, it is by no means invariable. In fact, never more than an estimated thirty per cent of the drops on the surface at a given time tend to form the parallel rows expected from Andrade's dust studies. In general, a drop thrown off by a curtain either (1) coalesces with the main body of the liquid, (2) runs toward the node, (3) aligns itself with other drops in parallel rows perpendicular to the tube axis, (4) runs toward the curtain or (5) moves in a highly erratic path in the area between the node and the antinode. Each of these possible modes of behavior will be discussed separately.

By far the great majority of the drops produced by a curtain coalesce with the main body of the liquid as soon as they strike the surface or almost immediately after striking it.

The drops that are thrown the farthest by the action of the curtain and then remain on the surface most often tend to move toward the node. When the liquid was water, most of these drops collapsed upon reaching the node, through some would be carried past the node and a short distance toward the next antinode. The drops that passed through the node lost most of their momentum quickly and returned to the node where most of them also collapsed. Many more drops carried through the node when acetone was the liquid in the tube rather than water. Often the drops collected near the node and remained at this point in no particular order. They behaved very much as if they were tiny balls that had rolled into the trough at random. These drops can be seen at the node in Figures 25 and 26. Since the acoustic motion precisely at the node is zero and the motion in the vicinity of the node is small compared to that at an antinode, the vortex systems attached to the drops should weaken or disappear in the neighborhood of the node. This is probably the reason that the characteristically unceasing movement over the surface tends to disappear when the drops collect near a node.

Some of the drops follow the behavior reported by Howatson. That is, they tend to align themselves transverse to the tube axis in neat rows with each drop very nearly touching. These drops are kept apart by their common vortex as will be discussed later. On many occasions two or more rows would form and remain stable at a distance of approximately 1/5 wave length from the curtain. On other occasions these rows suddenly burst into curtains only either to collapse or run toward the original curtain where the two would coalesce. Only if the SPL was at a level sufficient to maintain a new curtain would the curtain thus formed persist. At other times, many of the drops would be continuously forming into these rows which, in turn, would run along the surface to the curtain and be drawn into the curtain; then new rows would form and repeat the process. At no time were these rows observed to be more than one drop high, as were the rows reported by Howatson and as might be anticipated by the experiments of Andrade with small spheres in a tube.

Still other of the drops fell between the curtain the area where the rows most often formed. These drops either joined the drops in the

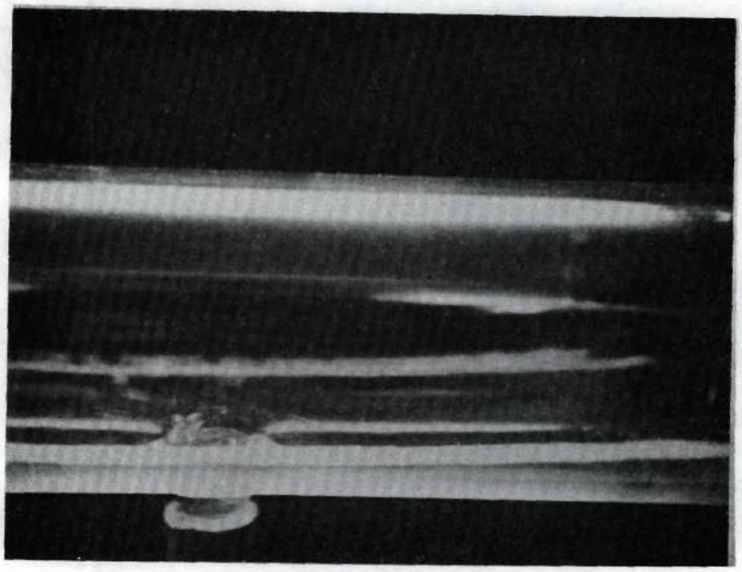


Figure 25. Water Drops Near a Node.

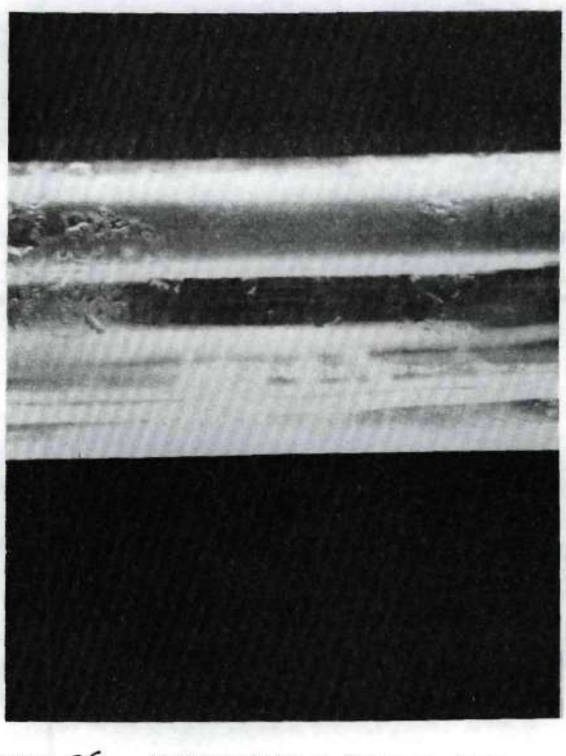


Figure 26. Water Drops Near a Node.

rows, individually moved to the curtain and disappeared, or, occasionally, moved in an erratic and seemingly random path over the surface of the liquid between the curtains and the area where the rows tended to form.

A variation of this behavior occurs occasionally when none of the drops appear to follow an ordered pattern. Instead, they move about over the surface of the liquid in very erratic paths "bouncing" off each other and behaving very much like a group of perfectly elastic billiard balls on a frictionless billiard table. These highly mobile drops move about in an area that extends to a point near the node and a point near the curtain, but not into either. The fact that these drops "bounce" off each other is explained by the vortices found by Andrade to be attached to the surface of objects placed in a resonant acoustic field as shown in the photographs of Figure 16. Andrade found that a sphere placed in a resonant acoustic field had, after a critical intensity was reached, a pair of cylindrical vortices attached to its upper surface and another pair attached to its lower surface. Of course, the lower pair is compressed in the case of the drops on a surface. Thus, there is an attraction between drops when the drops are separated and there is a repulsion when the vortex fields of two drops overlap. Therefore, there is a critical distance for which the vortices of the drops are in equilibrium. On some occasions the drops share a mutual vortex instead of separate vortices as is the case for the drops which form the transverse rows. This common vortex explains the fact that the drops in the transverse rows are close but do not touch. The repulsion when separate vortices are formed explains the regular spacing of the rows of drops. Howatson gives a brief, but highly informative, discussion of the effect on drop behavior resulting from attached vortices and relates this behavior to the studies of Andrade.

The effects studied by Andrade are much more likely to prevail when drops are present and the curtains are absent as obtained by the procedure outlined earlier in this section. Apparently, Howatson did not study the drops under these conditions. Nevertheless, the drops do follow very closely the behavior that might be predicted from a study of Andrade's experiments with tiny spheres in a tube containing only a resonant air column except, as mentioned before, they were never observed to be more than one drop in depth even when rows formed.

When only a single drop, or perhaps two drops, are maintained on the surface, their behavior is somewhat more difficult to understand and to relate to Andrade's experiments. These isolated drops tended to remain in a narrow band of tube length whose center was approximately 1/5 wave length from the antinode along the tube axis. This band extended completely across the tube. These drops moved very near the tube wall, (probably separated by the thickness of the vortex), where they would remain for a short time. Then, they would move across the tube -- sometimes slowly and sometimes rapidly -- where they would again temporarily come to rest near the opposite wall and then move across the tube once more. The path of a drop never appeared to be perpendicular to the tube axis. Instead a drop appeared to zig-zag toward the node until it reached the end of the band in which it was operating, and then it "zig-zagged" away from the node to the opposite limit of its band of operation repeating this process until it disappeared.

Occasionally the drop appeared to collide with the wall with sufficient force to break the vortex system and overcome its own surface forces, causing the drop to collapse. Also, when two or more drops were on the surface they occasionally collided and either coalesced into one drop or collapsed. However, the most common disappearance of the drops took place at an almost imperceptible rate. The liquid appeared slowly to be absorbed in minute amounts into the main body of the liquid with the drop systematically becoming smaller. Drops estimated initially to be 1/16 to 1/8 inch in diameter have been observed to shrink to almost imperceptibly small drops and, apparently, still retain their generally spherical shapes. However, a drop loses its mobility as well as most other features of its behavior as it becomes very small. Eventually, tiny drops collapse.

Deposits in the Resonant Tube

Deposits in a Smoke-Filled Tube

During some of the preliminary studies when the tube contained only smoke and air, an interesting deposit of particles formed on the bottom of the tube. Such deposits from tobacco smoke were mentioned by Andrade and others. Both the formations and the procedure for obtaining them differ in this work from those of previous investigators. Andrade employed a closed, smoke-filled tube, whereas the smoke used in the present study was allowed to pass through and out of the tube. The photograph of Figure 27 shows the deposits formed in a 2-3/4 inch I.D. tube resonated at 505 cps with an SPL of 152.1 db. For this photograph the smoke was blown from the tube and the tube rotated through 90 degrees so that

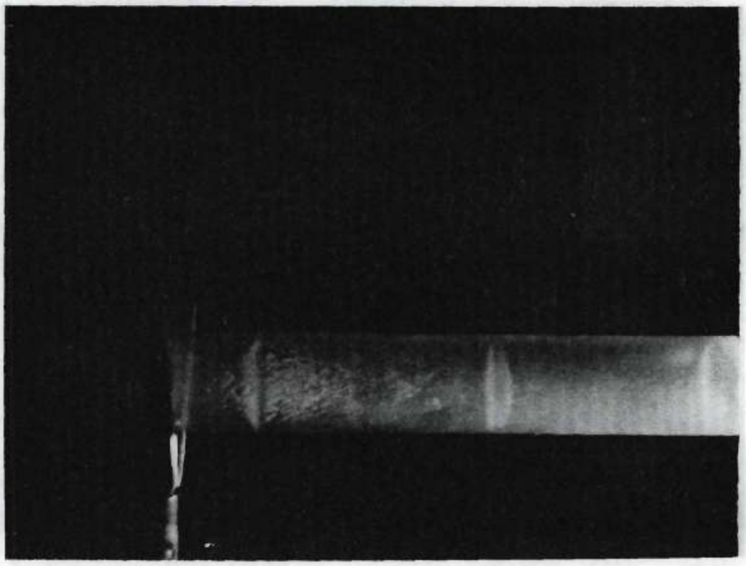


Figure 27. Deposits of Smoke Particles on the Bottom of a Resonant Tube. Here the Tube Has Been Rotated Through 90° for Viewing.

the bottom of the tube faces the camera. The smoke entered a small port located at the far right in the photograph and very slowly proceeded to the left along the tube and out of the partially open end where the horn was located.

The closed end of the tube is, of course, a velocity node. Thus, the equal spacing on the tube wall clearly shows that the deposits of smoke particles occur at the nodes. This can actually be determined from measurements directly from the photograph of Figure 27. The deposits at the first node, i.e., at the closed end of the tube, were not as marked as they were at some of the other nodes. The second node shows a neat, closely spaced arrangement of the particles. The next node shows an additional deposit of particles distributed outside the narrow band marking the node. It can be seen from the photograph that these deposits begin very near the second antinode and grow rapidly in number as the second node is approached. Also, it can be judged from this photograph that the number of particles deposited at this node is less than the number deposited at the previous node. In fact, the number of particles deposited diminished from node to node with most of the particles being deposited at the first two nodes past the inlet node. The fifth node showed only faint signs of deposits, and no deposits were detected at the nodes near the open end of the tube.

No attempt was made to determine the filtration efficiency of this phenomenon, but the absence of particles at the nodes near the smoke exit testifies to the fact that a resonant tube effectively filtered at least the larger particles. The smoke was produced by "filter" cigarettes. Andrade made no mention of this effect since his smoke was uniformly distributed and his particles could be expected to be uniformly deposited on the floor of the tube.

The deposits at the closed end of the tube do not appear in the photograph since the light was reflected so greatly by the thick plexiglass employed to seal the tube. However, this deposit was also interesting for it appeared as one-half of one of the patterns shown at the nodes in Figure 27. This clearly implies that the vortex formation located between the nodes deposits some of its particles at both of its bounding nodes and that the slight ring in the center of each nodal deposit corresponds exactly to the node. Measurements also confirm this.

Another confirmation is afforded by the photograph of Figure 28 where a faint ring of stationary smoke can be seen at the node in the left of the photograph. This ring was difficult to photograph, but it was noticed on many occasions when the tube contained only smoke and was resonated at high db levels. This smoke ring will be discussed further at a later point in this chapter.

Deposits in a Tube Containing a Salt Solution

A supersaturated solution of salt and water was resonated in the 1-3/4 inch diameter tube at various levels of tube SPL. Even though the solution had been filtered before placing it in the tube, salt deposits were formed. One of these deposits is shown in Figure 29 where two parallel rows of salt particles can be seen. These deposits were formed at 694 cps and were located between the node and antinode. Such deposits took as much as twenty to thirty minutes to accumulate.

These deposits were not as neatly outlined as were the particles produced from the smoke. Each deposit was approximately 3/8 inch in width and extended approximately 3/4 inch transverse to the axis and

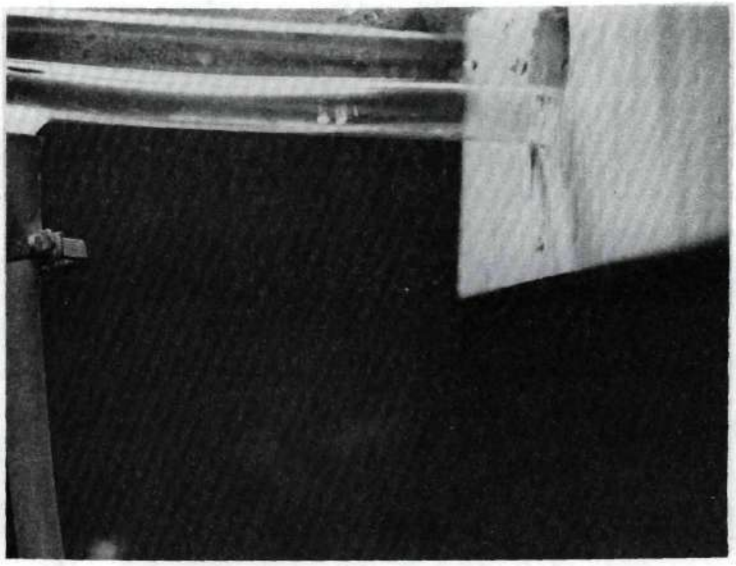


Figure 28. Salt Deposits on Bottom of Resonant Tube.

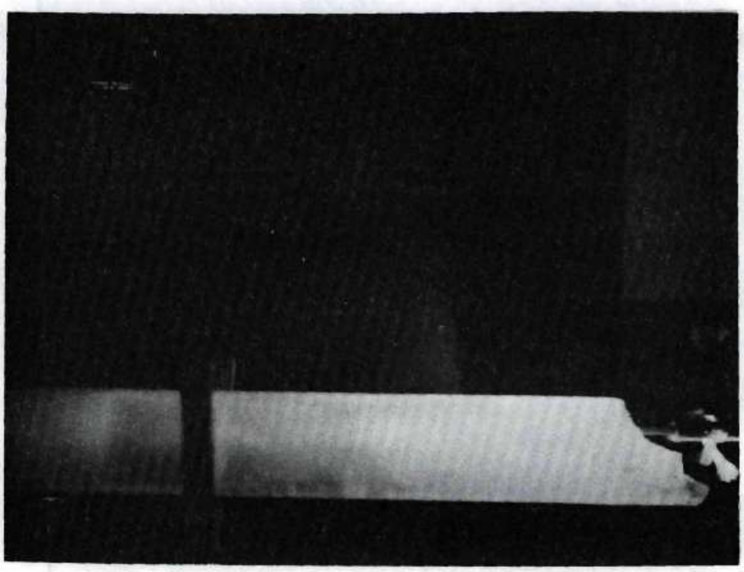


Figure 29. Smoke Ring at Node of A Resonant Tube.

along the curved wall. The deposits were several particles deep, perhaps as much as 1/32 to 1/16 inch.

Other Deposits in a Resonant Tube Containing a Liquid

When experimental tests for threshold correlations were made, distilled water was normally employed in the tubes. The tubes were thoroughly cleaned before a test. At other times ordinary tap water from a jug was used. Debris from the jug started a series of interesting observations.

Much of the debris has a specific gravity very near unity and did not settle readily. These lighter particles tended to follow the water currents when the curtains were in action. The sketch of Figure 30 shows some of the observed currents.

The heavier particles, unlike the salt, collected along the bottom of the tube at points very nearly, if not exactly, coinciding with the location of the nodes in the air above the water. In fact, the zero velocity of the air at a node appeared to extend down into the liquid so that the liquid also had zero velocity at this point. Thus, when the debris reached one of these points of zero velocity, it lost its momentum and settled to the bottom of the tube.

Miscellaneous Observations

Smoke Rings in a Resonant Tube

The photograph of Figure 29 as previously mentioned shows a stationary disk of smoke on a 2-3/4 inch I.D. tube resonated at 505 cps with a SPL of 152.1 db. This disk remained stationary and appeared to be located exactly at the node. If this is a result of zero velocity

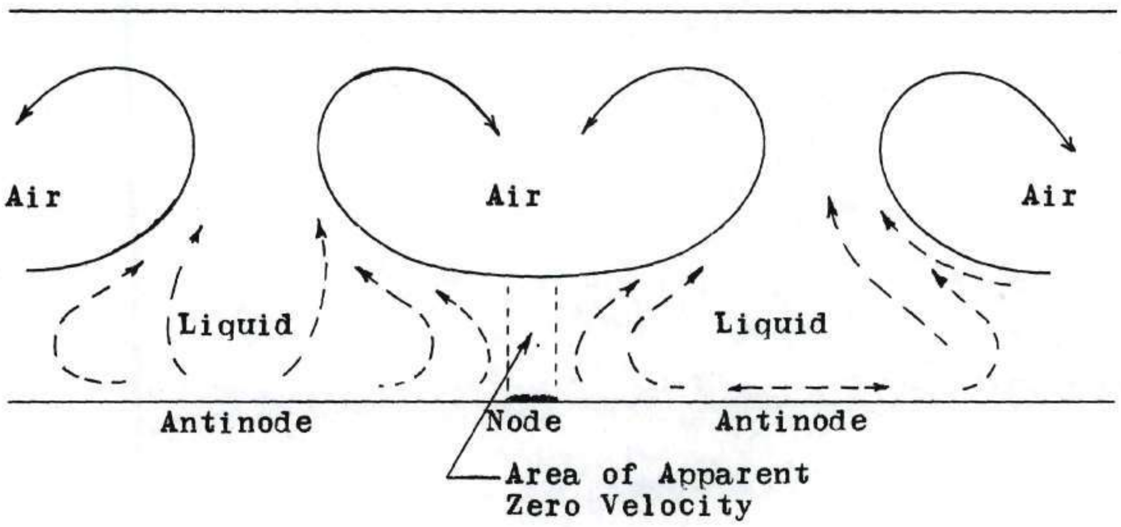


Figure 30. Particle Motion in Tube With Curtains.

at the node, then the physical width of the node is greater than might be expected for these disks were 1/8 to 1/4 inch thick. If the tube was allowed to resonate for long periods without any further addition of smoke, these disks became thinner and finally disappeared. However, there was always some general circulation noticeable in the tube and this can account for the thinning of the disks. On the other hand, the circulatory velocity (with regard to the vortex) of the particles near the node could possibly be so small that it takes considerable time for these particles to be moved into the main vortex on each side of the node.

Diamond Pattern on Acetone Surface

When a tube containing acetone was resonated at sufficient power level to produce the sinuous shape of the surface, but not sufficient to form curtains, a fascinating pattern appeared on the surface. A continuous, connected, pattern of tiny diamond shapes was distributed over the crests of the standing wave. The sides of each diamond were estimated to be 1/16 inch in length. The pattern appeared to begin about halfway between a node and an antinode and thus was approximately one-quarter wave length long with its center located at the antinode. No explanation for this phenomenon has been found, and no satisfactory photographs of the pattern were obtained.

Effect of Tube Length

Since viscous dissipation consumes some of the energy of the standing waves, it is not surprising that tube length can play a part in curtain formation. A curtain formed in a very short tube required a lower power input than a curtain formed in a long tube. However, it should be emphasized that, even though the power input was lower in the short tube, the SPL at the curtain was the same when a curtain formed.

Bands of Liquid on Tube Walls

A close examination of Figure 31 at the antinodes discloses a formation of rings or bands of fluid on the tube wall. These bands would often persist, to a reduced extent, even after the power was switched off. It often took considerable time for the bands to disappear after the power was turned off. The photograph of Figure 31 was obtained with acetone, since acetone exhibited a tendency to form bands to a much greater degree than did water. Only on a few occasions when the tube had recently been cleaned, would the water show these bands, and then only a few faint bands were visible. The fact that the water did not show these bands appears to be related to the fact that water would cling to the tube wall in large drops, whereas acetone was never observed to cling to the wall in drop form. Instead, the acetone formed a thin, almost transparent film over the tube surface at the points the liquid from the curtains struck the tube wall.

Other Interesting Formations

During the course of this research several other interesting formations were observed in resonant tubes. Since they are difficult to classify and since they deserve only brief mention, they will be presented together at this point.

Figure 32 shows a brief time-exposure photograph of partially unstable curtains of acetone in action. The reflected light gives the appearance of smoke in the tube and clearly shows the area of action of these curtains. The light regions are the antinodal areas. Actually, the curtains did not move to the limits of the light areas in the

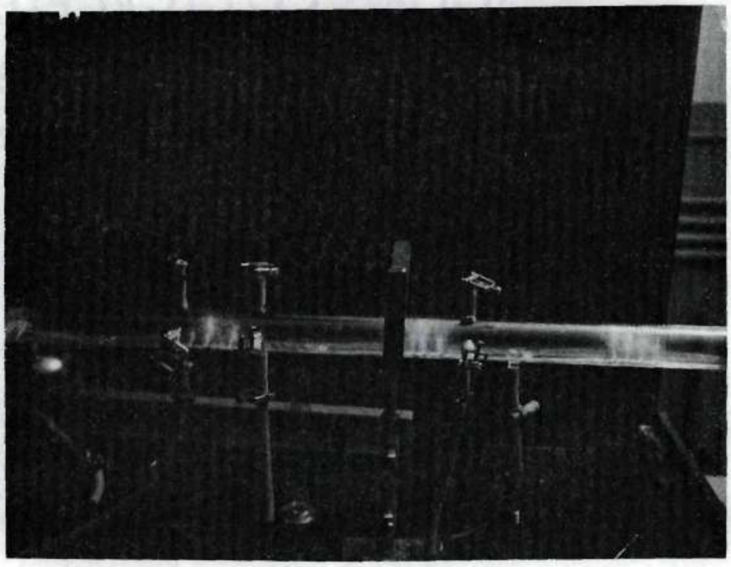


Figure 31. Multiple Acetone Curtains in Action Showing Bands on Tube Wall.

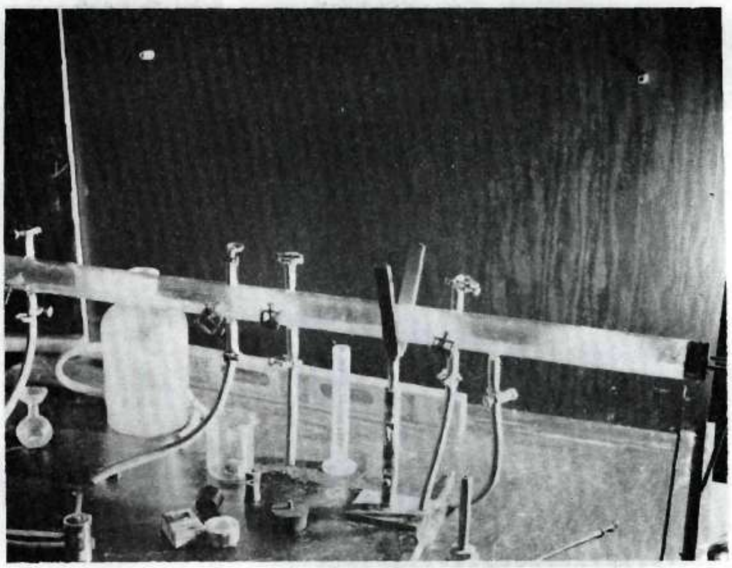


Figure 32. Time Exposure of Acetone Curtains in Action.

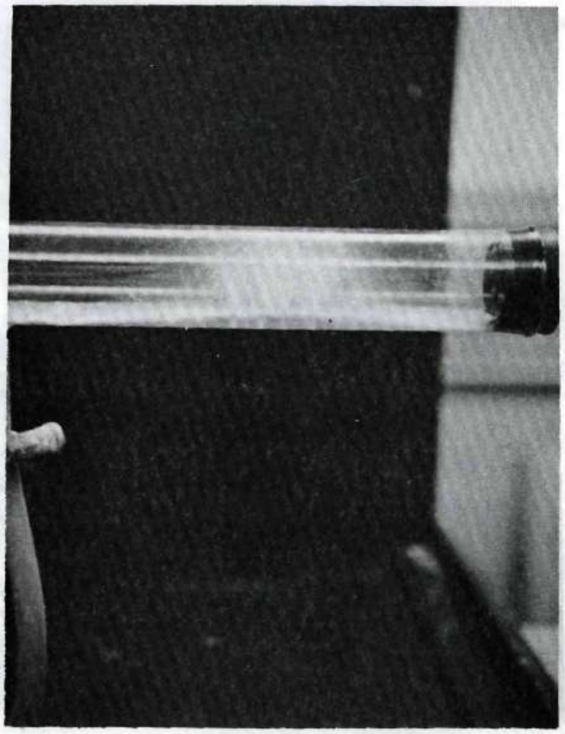


Figure 33. Multiple Acetone Curtains Showing Effect Beneath the Liquid Surface.

photograph. Instead, the fine spray from the acetone curtains reflected the light and resulted in the area of motion appearing to be larger than it actually was.

Another interesting formation resulted when the drops of ethylene glycol as previously discussed were placed in the water. The tube immediately filled with films and the primary effects were then located in the vicinity of the horn. Several pseudo-curtains, or films, were in action very near the horn. These films generated some strange tablet-shaped, or globular, formations which were most often sucked beneath the surface, circulated back to the curtain and again swept into the curtains. It was not possible to determine the exact nature of these formations, but they probably contained air and foam generated in the curtains.

Figure 33 shows multiple acetone curtains in action. Here, the interesting point is the effect of the curtains extending beneath the surface. This effect was not usually visible, especially for a single, stable curtain. The effect appears to arise from light reflected by the fluid in motion directly beneath the curtain.

Desalinization Studies

When this research was first undertaken, it was hoped that the known effects of stress in a liquid on concentration could be exploited to obtain significant gradients of salt concentration in sea water when the sea water was resonated in a Kundt's tube. Some initial experiments employing sodium chloride dissolved in distilled water held some promise. However, when the equipment was improved and sea water was employed the results were disappointing.

Samples taken from the sodium chloride-water mixture at various points in the mixture while it was being resonated showed no variation in salinity from point to point along the tube. The relative salinity was determined by comparison of specific gravities accurate to four significant figures. However, if the sample was resonated for long periods of time, there was usually some precipitation of salt from the solution, and deposits such as those of Figure 30, previously discussed, were formed. Thus, there appeared to be little variation in salinity from point to point, but some lowering of the salinity in general must have occurred.

On the other hand, when a sample of pure sea water was employed in the tube, there was no precipitation of salt from the water; or, if the normal debris precipitated from the sea water contained some salt, it did not lower the specific gravity of the sample enough to be of significance.

Since the sodium chloride-water mixture was well-filtered before a sample was placed in the tube, the reason for the difference in behavior between this mixture and pure sea water possibly warrants further consideration. This line of research was not pursued, however, for it was not the objective of this research unless preliminary experiments held real promise of developing a commercially feasible process of desalinization.

CHAPTER IV

FORMATION OF WATER CURTAINS

The previous chapters have indicated the strong interest that has been shown through the years on the formation of dust disks or curtains as well as the forces acting in a Kundt's tube containing only air. Interest in the phenomena of water curtains and the forces in the Kundt's tube containing water has also been made manifest. Two aspects of curtain formation will be presented in this chapter. Comments on the forces in the Kundt's tube will be found in Appendix A.

The two aspects of curtain formation are believed to be significant in two completely different respects. The first is perhaps the most important for it presents the first correlation of the physical conditions inside the tube which determine the "threshold" of curtain formation and it is not as speculative in nature as is the second. This correlation is presented in terms of easily measureable physical properties. The second aspect really amounts to comments on the difference in the observed behavior of dust curtains and water curtains as well as speculation on the manner in which water curtains form. The most important part of this discussion is the proposal that the type of behavior noticed by Jackson and Johnson is not due to convection alone but is due, at least in part, to higher order modes of vibration.

The first section of this chapter is therefore devoted to answering the question: Under what measurable conditions do water curtains first form? The second section will, perhaps, contribute toward the ultimate answer to the question: Why and how do water curtains form?

Threshold of Curtain Formation

Preliminary Investigations

During the early experimental and observational stages of this research, an intuitive relation between the power input to the various tubes and the "threshold" at which curtains first appeared in these tubes was developed. However, all efforts to obtain a meaningful correlation proved fruitless; for the points of power input seemingly fell at random on any plot of the variables involved.

These attempts led to another correlation that, though unsatisfactory in answering the basic question, led eventually to the variables truly of interest as well as the importance of using the conditions of acoustic intensity, or SPL, instead of power input as the correlation criterion. This preliminary correlation will be described before the presentation of the final correlation of curtain threshold conditions. This description is of interest as one of the steps leading to the final correlation, and is also a matter of interest in its own right.

Even though a correlation with power input could not be found for the conditions under which a curtain first formed, it was noticed that if the resonant frequency and water level in a given tube were held constant, then there appeared to be a relation between the number of curtains formed and the power input to the tube. With no other justification, a correlation relating the ratio of the number of curtains actually formed, N, to the number of crests in the tube, N_p, and the power input was attempted. This preliminary correlation is presented in Figure 34. This figure reveals that it is not satisfactory in terms of a general correlation. Nevertheless, a thorough study of the conditions leading to this partial correlation led to a better understanding of the controlling variables and eventually to the desired result.

Several points of interest concerning this preliminary correlation merit brief discussion. First, it should be pointed out that there is, apparently, a separate curve for each water level and each resonant frequency. Only two frequencies with two water levels for each frequency have been presented for purposes of clarity. Two ratios of depth of water, d, to tube diameter, D, for each tube were arbitrarily selected in presenting these curves. The two ratios of d/D for each of the two frequencies were chosen to give good separation of the two curves for each frequency when plotting the data. When the water levels for a given frequency in the tube are very close the curves tend to coincide.

The fact that the curves for a given value of d/D did not coincide leads to the suspicion that perhaps the SPL and not the power input must be employed in any final correlation. Another aspect of these curves is the vast difference in slope between the two values of d/D at 691 cps while the slopes for the two values of d/D at 825 cps appear to be very nearly equal. This type of behavior occurred at some values of d/D and frequency but not at others. Of course, this indicates that the parameter d/D is not of fundamental importance in governing behavior or that some other parameter of importance has been omitted. The curve for a given value of d/D was reasonably reproducible, but great care was necessary in obtaining the same water levels if the values of N/N_p were to be reproduced at the same power level for similar experiments.

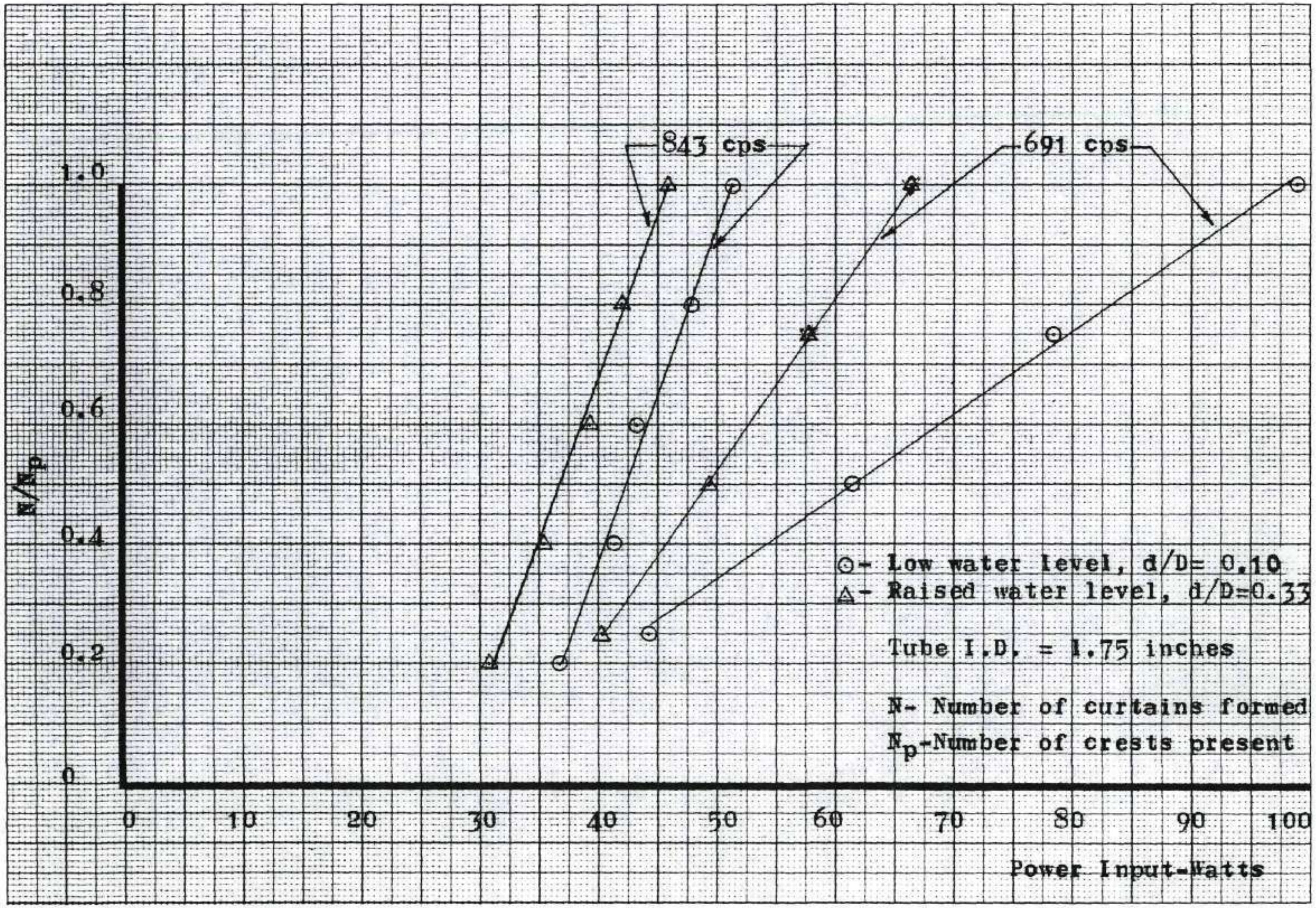


Figure 34. Curtain Formation-Preliminary Correlation for Water.

The straight-line relation between power input and curtain formation leads to speculations concerning the behavior inside the tube when a curtain forms. The existence of vortices in the tube at the time of curtain formation appears to be well established. Andrade, as well as other investigators, established the effects of vortex formation on the dust striations in a tube as well as the probable effects of vortices on the formation of dust curtains. Thus, since each vortex represents a certain amount of energy, it seems possible that the various points on the straight line of Figure 34 represent conditions at which pairs of vortices attain an energy level necessary to form a curtain. That this is the energy related to a pair of vortices follows from the fact that a vortex formation exists on each side of a curtain. It is possible that there is a matched pair of vortices on each side of the curtain. However, the last section of this chapter presents an argument that indicates the formation of a large vortex instead of a set of small ones between a node and antinode when curtains are formed.

Although relations concerning the number of curtains formed appeared amenable to correlation if pursued, this was treated as preliminary to one of the basic intents of this research. That is, the precise conditions under which a curtain first appears at a given resonant frequency was considered to be the basic intent of this phase of this research.

Final Correlation

It was first assumed for the sake of thoroughness that both wave length and frequency (which can be related through the temperature dependent sound velocity) water depth, tube length and tube diameter were variables of importance. These were included in the early investigations along with the variables finally chosen as the controlling variables. However, it was eventually determined that either wave length or frequency, but not both, were significant, and that the other variables, i.e., water depth, tube length, and tube diameter, did not play an important role when the actual conditions in the tube were employed in the analysis.

A dimensional analysis of the variables finally chosen as significant (see Appendix C) yields the following parametric equation:

$$\left(\frac{P_{max}\ \mu^2}{\rho\ \sigma^2}\right) = C \left(\frac{\rho\ \sigma\ \lambda}{\mu^2}\right)^n , \qquad (4\text{-}1)$$

where P_{max} is the maximum change in pressure within the tube due to sound (i.e., pressure amplitude), λ is the wave length, ρ is the density and σ is the interfacial tension of the liquid with air.

A preliminary correlation involving only the variables P_{max} and λ is shown in Figure 35. It can be seen that the data for water fit one line reasonably well and that of acetone another, separate line. That the data for water falls near the same straight line in this particular case is the result of the temperature of the water in the runs shown on this curve being constant within two degrees Fahrenheit. This figure readily shows that the longer the wave length and thus the larger the vortex, the greater is the energy necessary to form the first curtain.

The final correlation is presented in Figure 36. This correlation includes all the properties determined to play a major role in curtain

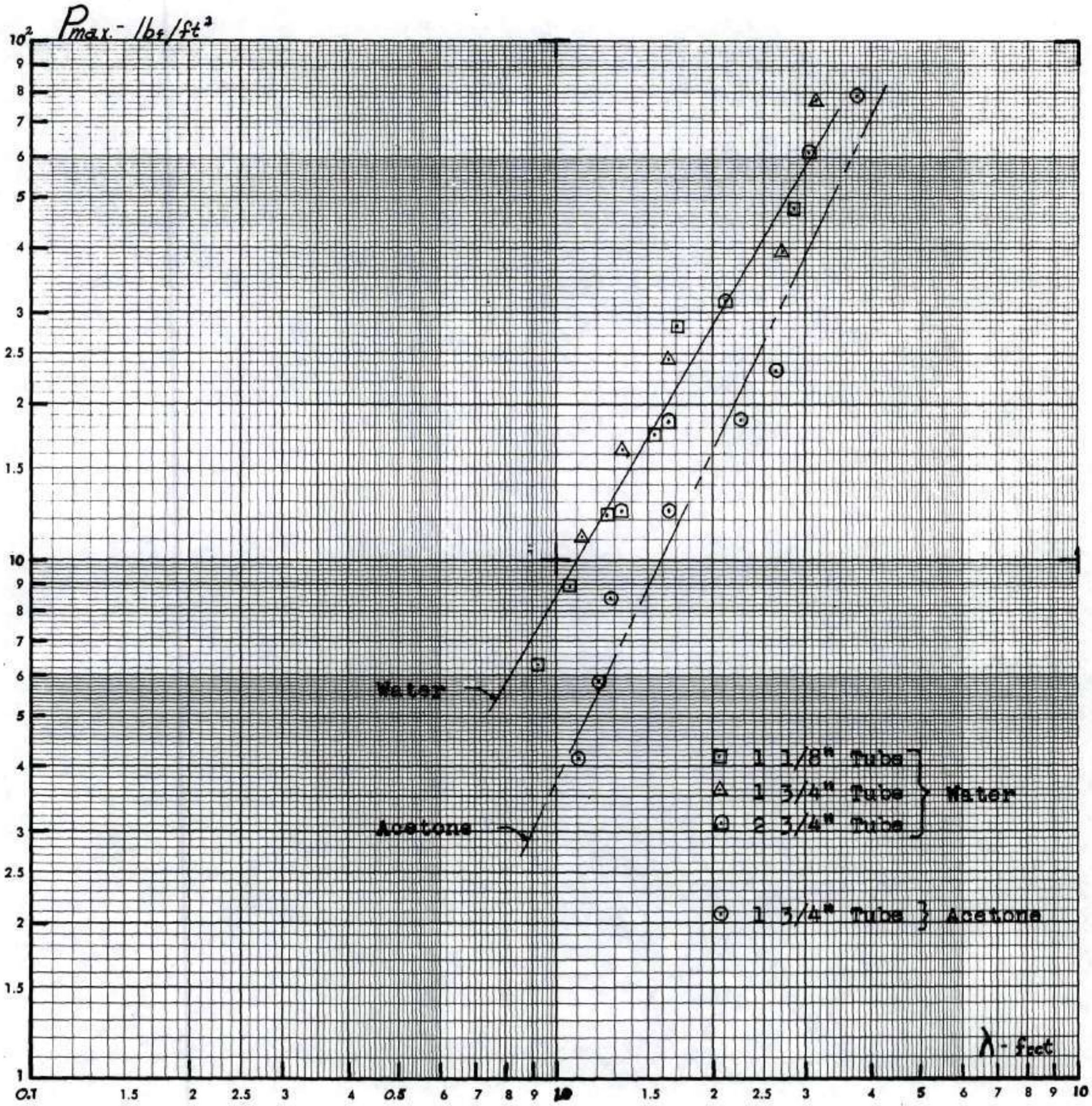


Figure 35. Curtain Formation Threshold - Preliminary Correlation

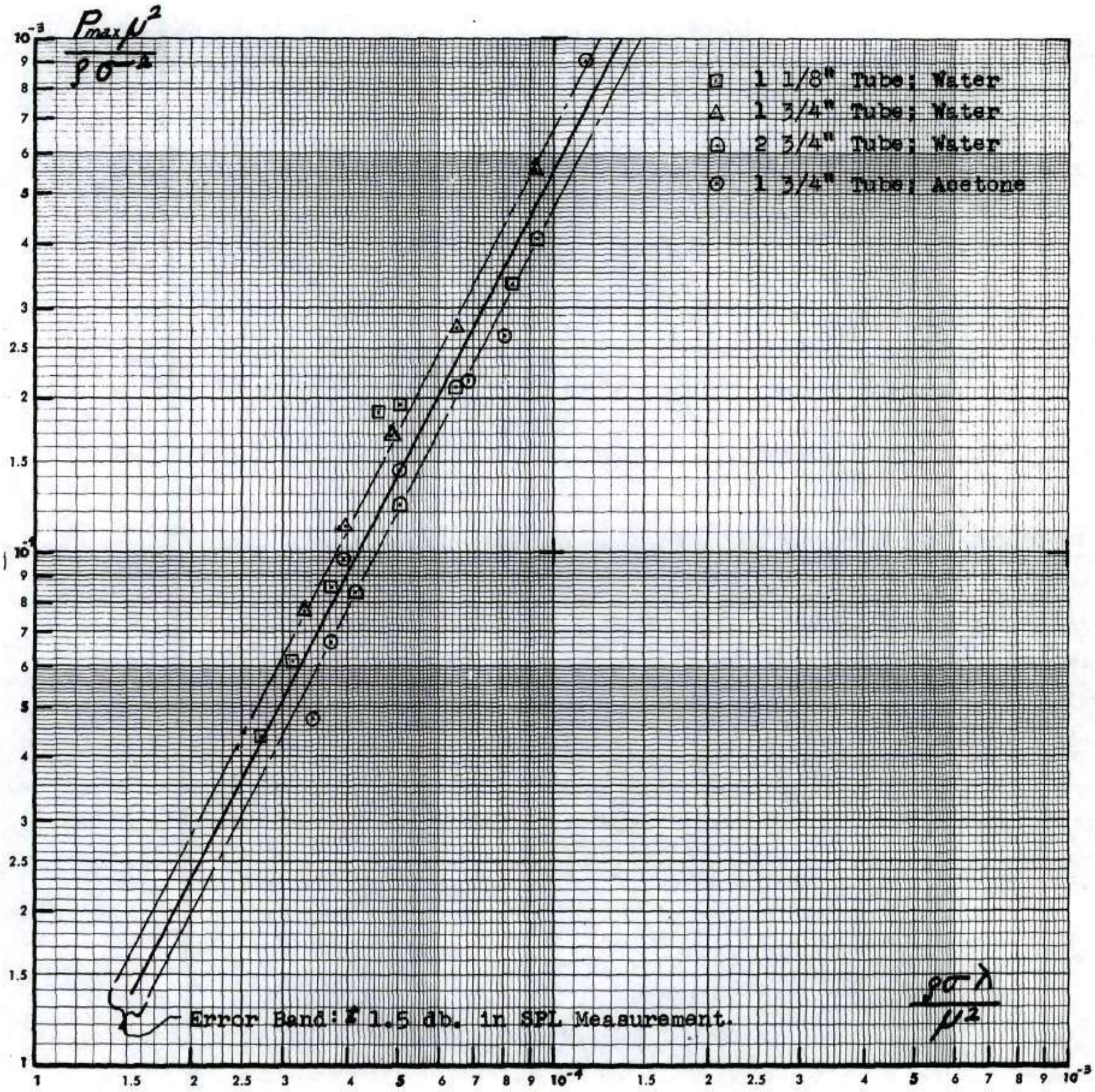


Figure 36. Curtain Formation Threshold Correlation.

formation. The solid line indicates a fit of the data according to the following equation:

$$\left(\frac{P_{max}\ \mu^2}{\rho\ \sigma^2}\right) = 32,600\left(\frac{\rho\ \sigma\ \lambda}{\mu^2}\right)^{1.945} \qquad (4\text{-}2)$$

The broken lines give the error band for the data. It was estimated that an error of $\pm$ 1.5 db. existed in the measurement of the value of SPL. An examination of the figure shows that 82 per cent of the data points either touches or lies entirely within this band. It should be noted that due to the nature of the relationship between SPL and P_{max}, an error of $\pm$ 1.5 db. does not represent the same percentage of error as does -1.5 db. (see Appendix B for this relationship).

The method of relating P_{max} to SPL is given in Chapter V and Appendix B. The data from which all of the curves of this chapter were obtained are given in Appendix B.

Discussion of the Physical Aspects of Curtain Formation

Both the experiments in an isothermal tube and the theoretical developments of Rayleigh[2] and Purdy[5] for secondary flows under the influence of an acoustic field indicate matched vortex cells symmetrical about the axis of a resonant tube. Such a system is shown in the photographs of Figure 3 and again schematically in Figure 4. Many of the investigators have over the years mentioned the difficulty of forming these cells in an undistorted state. They explained the steps taken to eliminate distortions believed to be the result of non-isothermal conditions. Usually a water jacket of some nature was placed about the test section. However, it was not until Jackson and Johnson's[13] investigations in 1960 that a different type of vortex was clearly formed. These investigators produced a startling difference in the vortex formation as is shown in the photographs of Figure 8 and schematically in Figure 9. A photograph of a state that appears to have the two types of cells mixed is shown in Figure 37. Here, there appears to be a dominant formation of vortex cells across the entire tube with a pair of smaller vortices trapped in the larger formation.

Jackson and Johnson attribute this difference in behavior to the existence of convection currents in the non-isothermal tube. Their calculations indicate that a considerable rise in temperature can be expected at the antinodes due to frictional effects, depending upon the SPL in the tube. Jackson and Johnson presented a sketch of the two types of vortex cells. Their sketches indicate, as do the sketches herein, that opposite directions of circulation can be expected for the two types of vortex formation. However, they did not give any particular significance to this observation[28]. This fact was pointed out in the thesis of Sanders[7], but he, too, placed no special significance on this difference in circulation even though he does, at one point in his thesis, place emphasis on the difference in direction of the circulation of water curtains and dust curtains, as did Howatson.

Even though some investigators have attributed the type of motion first noticed by Jackson and Johnson to convective currents, it appears much more likely that this is not the fundamental explanation. Basic vibration theory considers the excitation of other modes of resonance

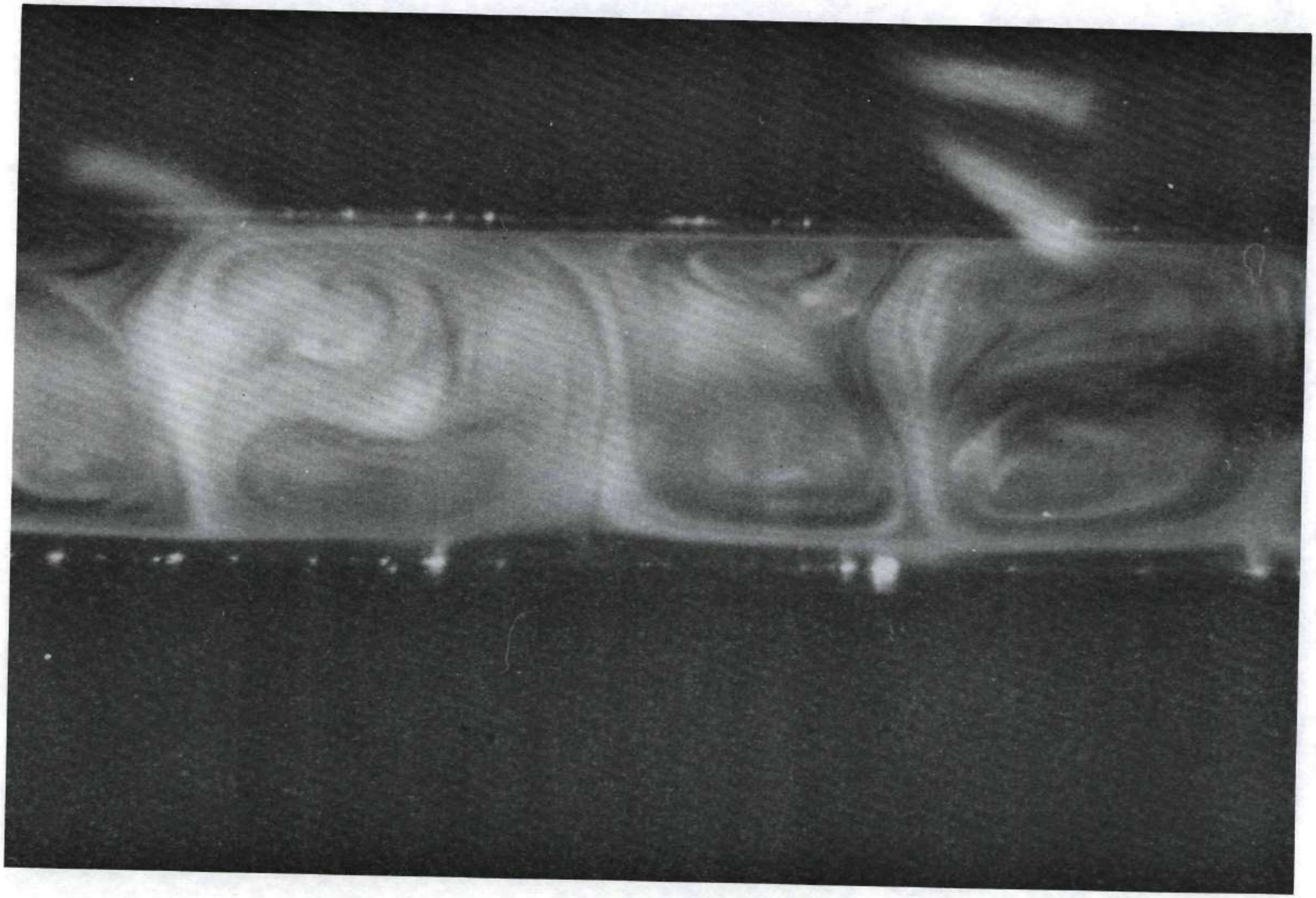


Figure 37. Non-Isothermal Cells Containing Smaller Vortices.

under certain conditions, (i.e., modes other than the basic longitudinal vibration of the particles). Some experiments conducted by Dr. Calvin C. Oliver[29] of Purdue University, strongly support an assumption that the basic changes in vortex patterns result from exciting an additional mode of vibration rather than convective effects alone. This, then, might also account for other types of vortex motion, e.g., the mixed behavior shown in Figure 37. Andrade first pointed out that "...the appearance of the various phenomena is mainly governed by the intensity of the air vibration...." when discussing the behavior of dust particles. He, of course, did not have the equipment of produce intensities great enough to excite the many modes of vibration producible today, but his remarks still apply. The inception of a new vibration mode can account for the sudden inception of some of the phenomena discussed previously. For example, Dvorak's[24,25] production of a short-lived spurt of liquid at a crest and the fact that he never produced curtains very possibly reflect his inability to produce the higher modes of vibration necessary to form a complete curtain. At most, he might have produced a brief vibration in this regime.

After the many hours spent in observing the behavior inside the resonant Kundt's tube, it seems worthwhile to speculate on a possible explanation of curtain formation. There are enough experimental observations from this and past research to justify the following tentative explanation, but not enough to prove conclusively the proposed theory of formation.

If it is true that curtain formation does not occur until the type of vortex formation first observed in detail by Jackson and Johnson has been generated. Then the vortex motion at the antinode is upward, as can be seen from Figures 9 and 38. This would mean that the vortices on each side of an antinode sweep across the water surface toward the antinode. The no-slip boundary condition requires a drag on the non-rigid water surface that will tend to move the upper layers of the water on either side of the antinode toward one another. As the two flows, traveling in opposite directions, meet at the antinode, their collision might well cause a crest to break in much the same way two water waves traveling in opposite directions break when they meet. This latter occurence is a matter of common experience and most people have observed the spurt of liquid that results when two waves meet. Now, when the vortex motion is strong enough to cause this break, the water is further lifted at the antinode by both the lowered pressure at this point and the continued drag of the vortex as it sweeps upward over the antinode. Observation of the path of the liquid drops in the larger tubes -- where all of the liquid does not strike the top of the tube -- leads to the postulate that the liquid follows the vortex path on a part of the liquid's path back to the surface. This further bears out the possibility of the existence of a large vortex when liquid curtains form rather than a pair of vortices having opposite circulations.

Many attempts were made to make the vortex formation visible above the water surface. All of them failed. When the tube contained enough water to form crests and curtains, then the water absorbed the smoke much too rapidly to allow any conclusive observations. This is unfortunate for it could possibly lead to helpful conclusions if the exact nature of the vortex formation could be observed immediately before and immediately

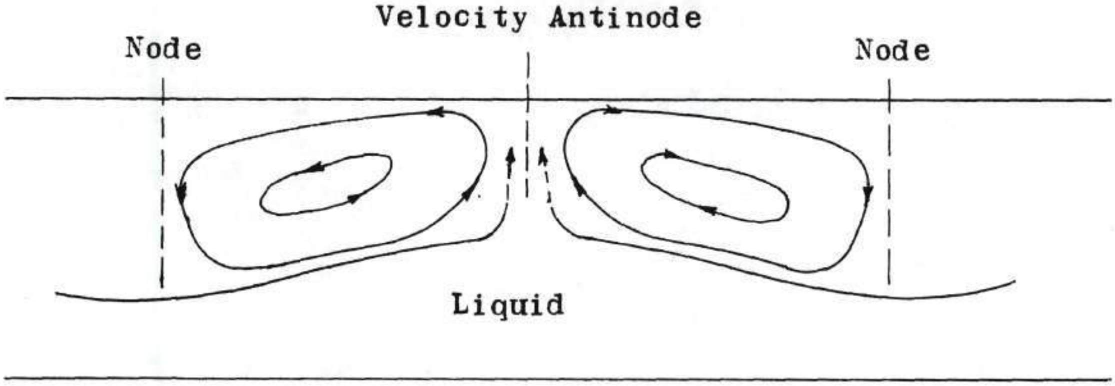


Figure 38. Non-Isothermal Vortex Cells and Liquid Curtain.

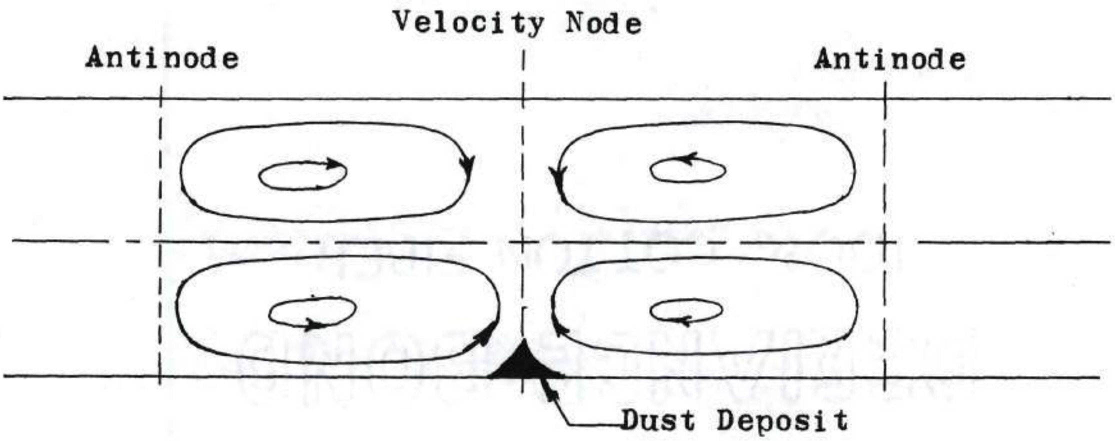


Figure 39. Isothermal Vortex Cells and Dust Deposit.

after the formation of a curtain.

One other point bearing on the speculative explanation of curtain formation might be made here. Howatson first pointed out, and it was observed many times in this research, that a surface ripple, or what might be characterized as a "pucker" or "wrinkle" of the liquid surface, often forms near an antinode and runs to the antinode where it bursts into a curtain. Perhaps this surface ripple is a manifestation of the type of crest that the surface drag would form and, further, it would then seem reasonable that it bursts into a curtain at the antinode due to the assistance of the lowered pressure at this point. Since it seems reasonably certain that this ripple is not a wave reflected from the end of the tube (it is not seen moving over the surface from one of the ends but is seen only as a sudden formation near the antinode) then it is more reasonable that this ripple was produced by the viscous interaction of the water and air at their interface. The fact that this ripple is not seen at the very top of the crest is explained by its always bursting into a curtain when it travels to this point or when it originates at this point. It appears that the ripples seen on the surface to either side of the antinode form at off-resonance conditions. Though experiment does not prove this conclusively, it does appear to bear this out for, if the system was deliberately set to slightly off-resonant conditions, these ripples often, but not always, formed. On the other hand, when the system was carefully set to the conditions believed to be exactly resonant, the ripple was never observed to form.

That the water curtain has a vertical direction of motion can be accounted for by this explanation. On the other hand, the downward direction of motion of dust can be accounted for as follows: When dust curtains are formed from a "dust" that has a density near that of air in a resonant tube, the dust is swept into the vortices and very nearly follows the motion of the pair of vortices formed when the first mode of vibration observed by Andrade dominates (shown in Figures 4 and 39). Here, one of the vortices has a downward velocity at this point. The combination of the downward momentum of the particles in one of the vortices plus the force of gravity should dominate and result in a general downward motion of the particles at the antinode.

Although this cannot be taken as definitive, it is believed to be of interest since it poses some explanations believed to be reasonable on the basis of observations. It also shows the manner by which some of the various phenomena that have been observed to occur in the Kundt's tube can be consistently explained. Perhaps, the most important speculation is related to the proposal that the different types of vortex motion and the inception of water curtains results from the excitation of a mode of vibration not observed by Andrade in his dust studies. If this is in fact true, then the possibility exists that as even higher intensities are obtained in tubes, and still other modes of vibration are excited, other startling results might be produced in the Kundt's tube.

CHAPTER V

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Instrumentation and Equipment

Geometry

Consideration of both a rectangular and a circular geometry led to the choice of circular geometry. The circular geometry was thought to have several advantages such as ease of obtaining samples in the desalinization studies, ease of matching the horn to this geometry as well as having the horn give a more uniform radiation, greater accuracy in leveling the tube, better photographic qualities and, most important, ready comparison with the previous work of Howatson[26].

Test Section

The test section is shown in Figure 40. In this photograph a 1-1/8 inch I.D. glass tube is shown in position on the adjustable supports. The test section was closed at one end either by Plexiglas or a hard rubber stopper. In either case, a small hole was drilled in the closed end to accept the sound pressure probe. The other end of the test section had a dam, usually constructed of Plexiglas, that partially closed the tube and served to keep the liquid in the tube. The horn was inserted above the dam in the free area. A filling tube was installed on the bottom of most of the tubes.

Special Test Section for Desalinization Studies

A special test section shown in Figure 41 was designed for the desalinization studies. The tube was first blown and cut. Then, guided

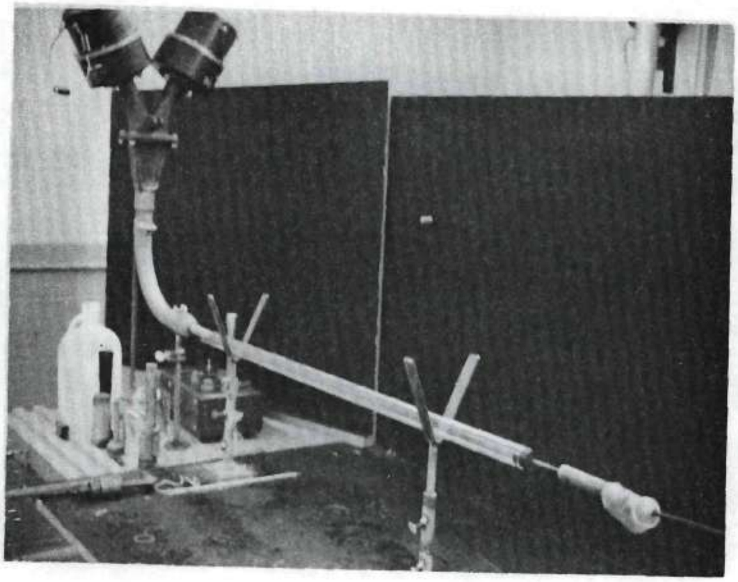


Figure 40. Typical Test Section With SPL Probe Inserted.

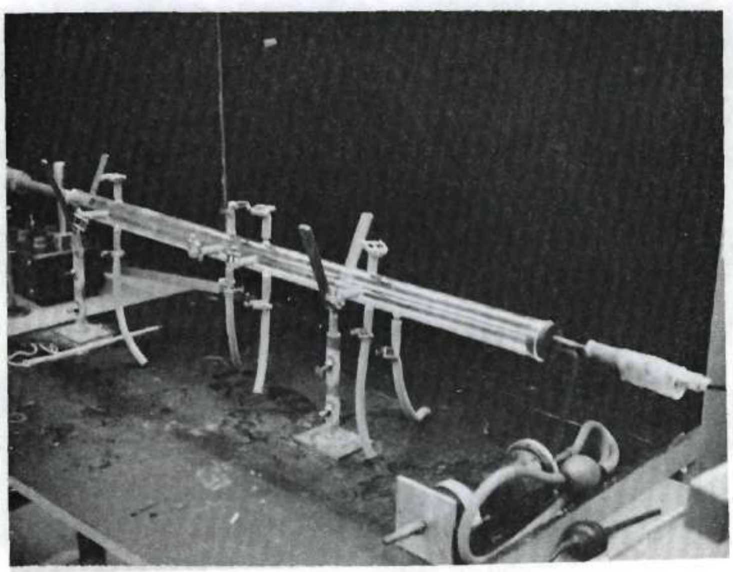


Figure 41. Special Test Section for Desalinization Studies.

by actual test conditions, points such as the top, side, and bottom of nodes and antinodes were marked at numerous resonant frequencies. An experienced glass blower then inserted taps at these points. Tests were next carried out to determine whether or not these taps affected either the SPL or resonant frequencies when a rubber tube, suitably clamped, was placed over these taps to close them. These tests indicated that as long as the taps were completely closed neither SPL nor resonant frequency was affected to any measurable degree.

The rubber tubing used to close each tap also served as the take-off for samples at the side and on the bottom of the tube. The side tap was usually near the top of the liquid surface, but, when it was not so located, a probe was inserted in the taps located on the top of the tube and samples were drawn from the surface of the liquid.

Light Sources

Several techniques of lighting were employed in obtaining the photographs for this research. The fluorescent lights in the laboratory provided a high intensity and uniform light for general photography. Special lighting effects were obtained by: (1) direct lighting of the test section with photoflood lamps, (2) indirect lighting of the test section by photoflood lamps, (3) lighting by the direct beam of a shaded flashlight and, (4) lighting by a strobe light aimed directly at the surface of the liquid.

Smoke Supply

The smoke employed was supplied by the smoke generator shown in the photographs of Figures 42 and 43. Figure 44 shows a schematic diagram of the unit. A bulb used for pumping the air through the smoke generator and

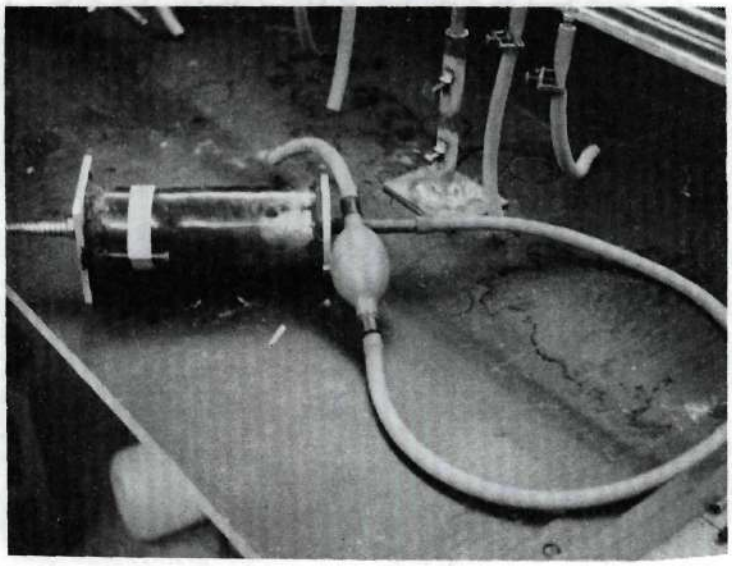


Figure 42. Closed View of the Smoke Generator.

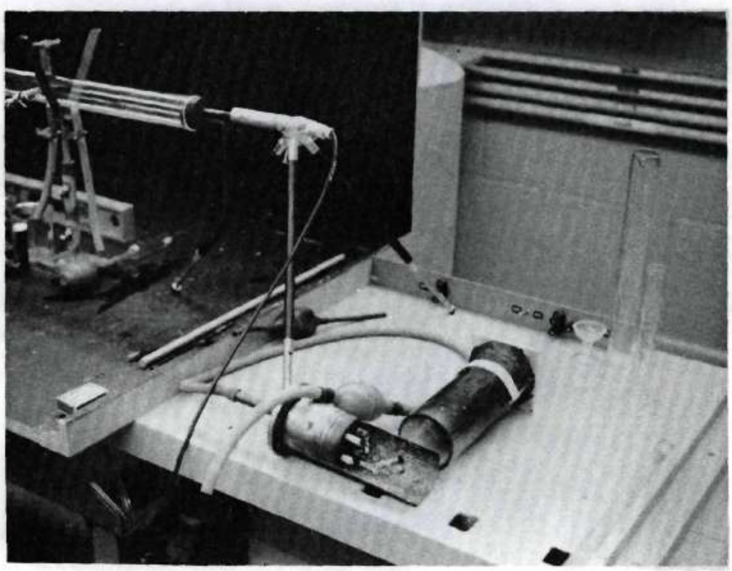


Figure 43. Open View of the Smoke Generator.

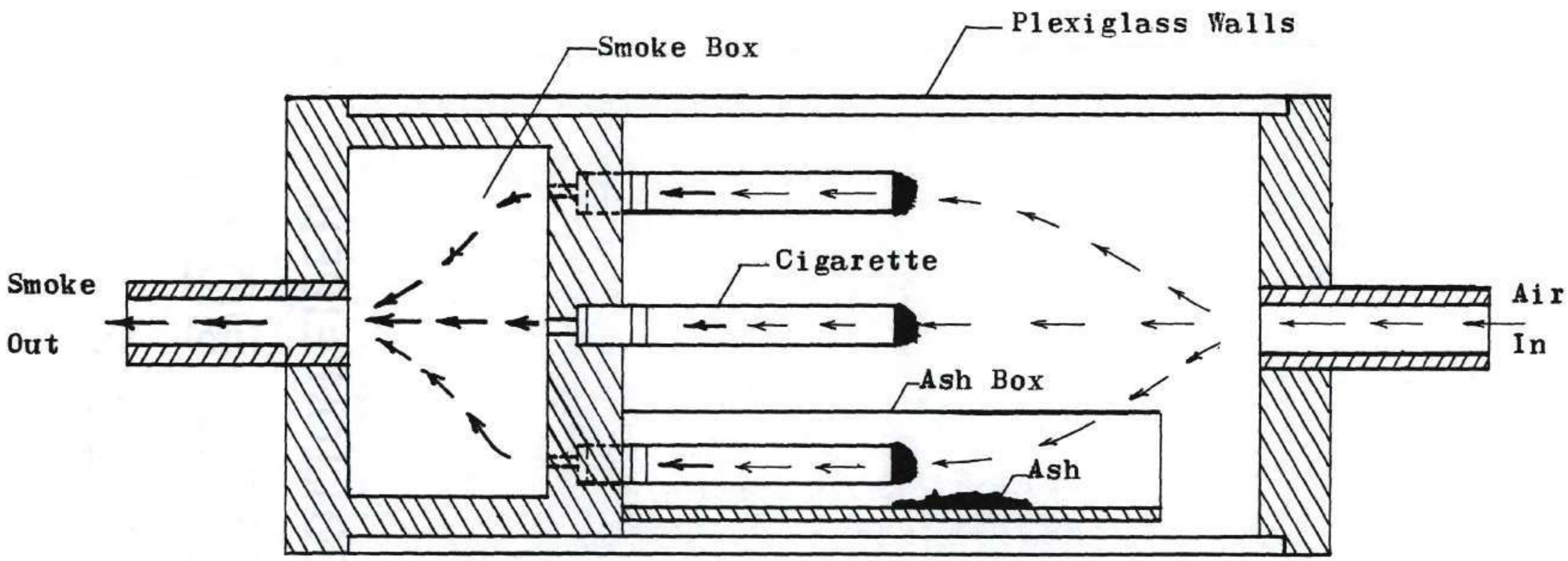


Figure 44. Schematic of the Smoke Generator.

the smoke into the tube can be seen in the photograph of Figure 42. The cigarettes employed in the generator were a standard "filter" brand.

This type of generator was first employed by Jackson and Johnson[13] for their smoke studies and later was used by Purdy[5] in his research. It consists of a 3 inch I.D. Plexiglas cylinder closed at one end by an inlet flange with a rubber tube fitting and at the other end by a smoke storage box. This box was provided with receptacles for five cigarettes and an ash tray to protect the Plexiglas cylinder. After lighting the cigarettes, the inlet flange was slipped into place, and air was pumped through the generator with the bulb attached to the test section supply hose. The cigarette smoke passed through the unburned tobacco and the filter; it then entered the smoke box; and was finally pumped into the test section.

Tar from the tobacco smoke deposited on the walls of the tube as explained in Chapter II and also in the water when water was in the tube. Consequently, it was necessary to clean the tube often. Also, water absorbed the smoke so rapidly that satisfactory photographs were never obtained of smoke patterns above the water. It was, however, possible to make some limited observations of the smoke patterns with water in the tube, even though photographs could not be obtained.

Sound Generating Equipment

The sound generating equipment is shown schematically in Figure 45 and in the photographs of Figures 46 and 47. A Hewlett-Packard, Model 206A, low-distortion, audio signal generator provided a source of continuously variable audio-frequency voltage at a total distortion level of less than 0.1 per cent. This signal was amplified by an Altec Model 260A

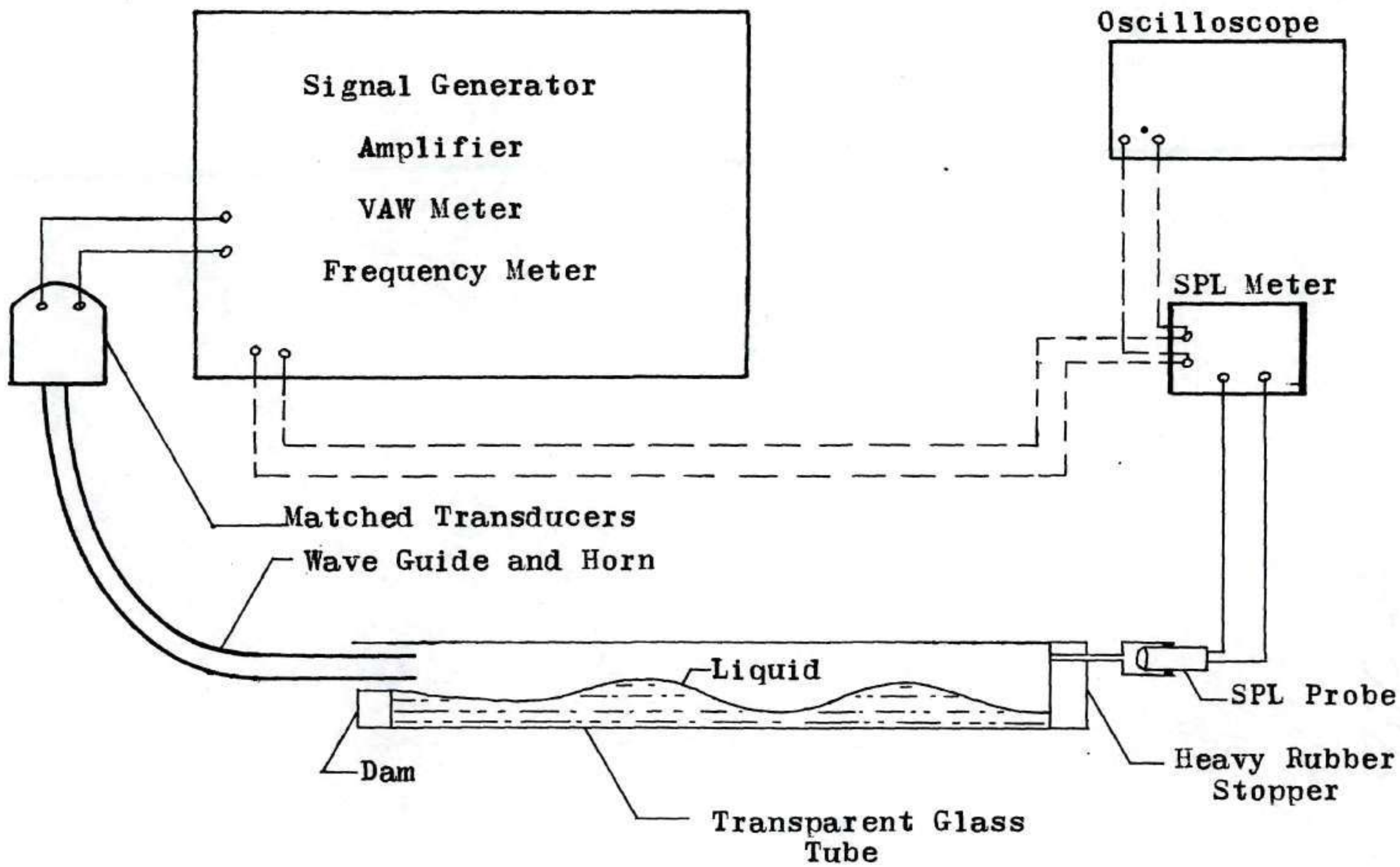


Figure 45. Schematic Diagram of the Experimental Apparatus.

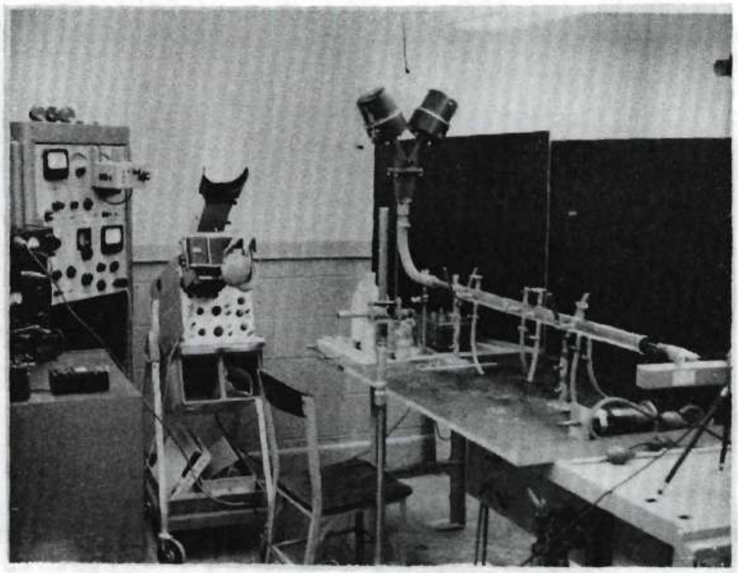


Figure 46. View of Experimental Equipment.

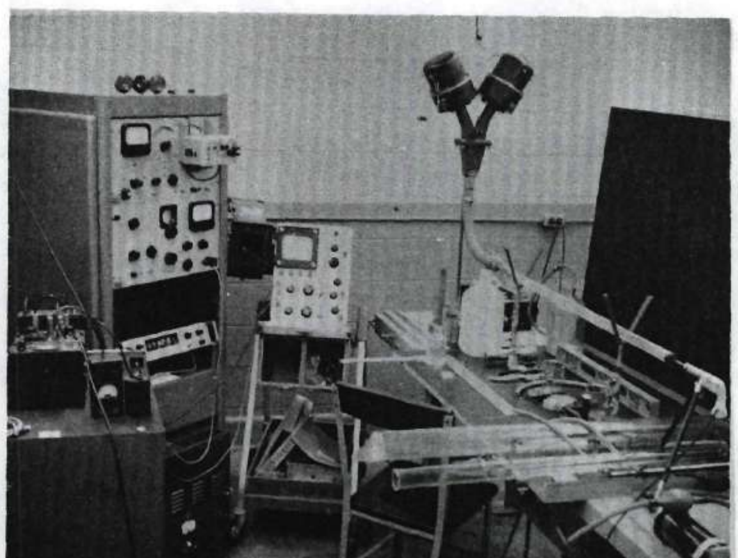


Figure 47. View of Experimental Equipment.

amplifier. The amplifier output voltage, current, and power were measured with a Fluke, Model 102, "VAW" meter. Electrical-to-mechanical conversion was achieved with a pair of Altec, Model 290D, driver-loudspeakers fitted to a throat adapter which was, in turn, fitted to a 1-3/4 inch curved tube. Various sizes of horns were attached to this tube depending on the diameter of the test section. These speakers had a frequency response of 20 to 20,000 cps and a power rating of 100 watts each when operated at a constant frequency. The speakers were occasionally driven beyond the rated power levels for short periods of time with no measurable distortion in the output signal.

Sound Measuring Equipment

The sound measuring equipment consisted of the following items manufactured and/or supplied by the General Radio Company:

Item	Type
Sound level meter	1551-A
Power supply	1262-A
High level microphone assembly	1551-P1H
20 db attenuator pad	1551-P11
Sound level calibrator	1552-B
Transistor oscillator	1307-A
10-foot cable	1560-P74

All of the equipment drew power from a Sorensen, Model 2501, voltage regulator.

In order to measure the sound pressure in the test section containing water, a special probe was constructed and attached to the microphone. In addition, it was necessary to provide a means for keeping the vapors from the microphone since it was highly sensitive to humidity. This was accomplished by providing a shield of latex rubber over the microphone. The probe is shown inserted in the end of the tube in Figure 40. Figures 48 and 49 show two typical power inputs and the associated outputs as registered by the microphone pickup and displayed on a dual-beam oscilloscope. Figure 48 is typical of all but a few frequencies with the input having little or no distortion and the SPL showing the same characteristic. However, for a small number of the resonant conditions (usually the lower frequencies), a distortion of the type indicated in Figure 49 was encountered where the output signal showed a distortion at the lower peaks. The photographs of these signals were taken directly from the viewing screen of a Tektronic, Type 502, dual-beam oscilloscope.

The sound pressure level, SPL, measured relative to 0.0002 microbars is defined as

$$SPL = 20 \log(P/0.0002) \text{ db} \tag{5-1}$$

where P is the r.m.s. pressure deviation due to the sound waves expressed in microbars. If the pressure and velocity are assumed to have the same relationship as they do for plane waves in an inviscid perfect gas undergoing resonant vibrations, then

$$P_{max} = \rho_\infty c_\infty U_o \quad . \tag{5-2}$$

If the expression for SPL is converted to pounds per square foot and solved for P_{max}, it becomes

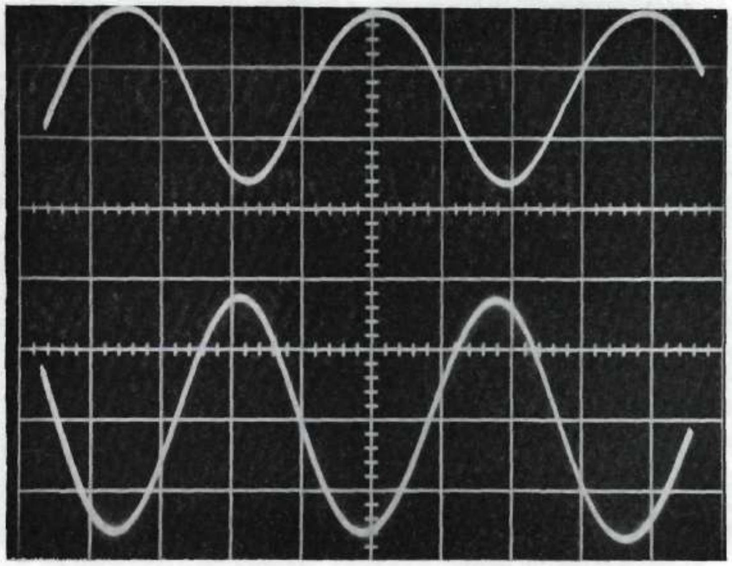


Figure 48. Power Input Signal and Probe Output Signal with Latex Diaphragm. Upper Curve is Input. SPL=165.3; f=365 cps.

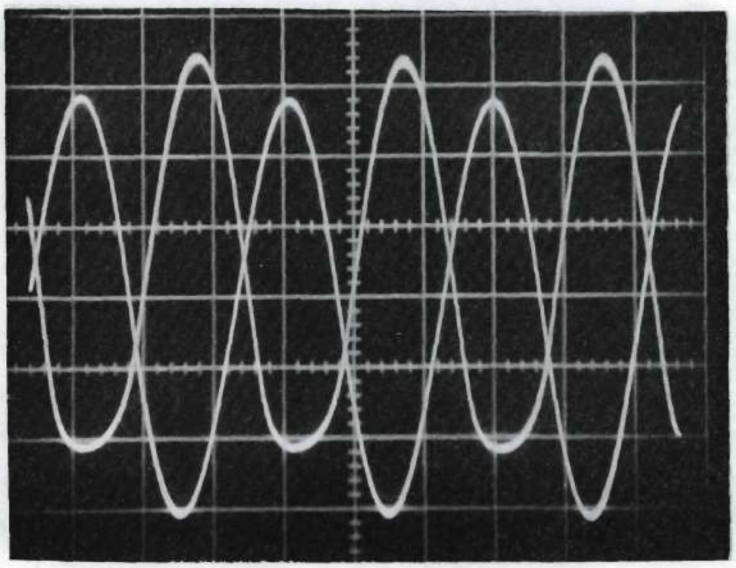


Figure 49. Power Input Signal and Probe Output Signal with Latex Diaphragm Showing Distortion in Output Signal. SPL=147.5 db.; f=533 cps.

$$P_{max} = 10^{\frac{(SPL - 124.6)}{20}} \quad (5\text{-}3)$$

where P_{max} is the maximum change in pressure due to sound.

Photographic Equipment

The photographs for this dissertation, with the exception of the oscilloscope screen, were obtained with a Polaroid Land Camera, Model 900. The photographs of the oscilloscope screen were obtained with an Alphax No. 3 shutter and a Polaroid roll film back. In all of the photographs, Polaroid Type 47 film, ASA No. 3000, was used. This film was fast enough to stop all of the motion encountered in this research. Time exposures were employed only to illustrate various points of interest.

Frequency Measuring Equipment

The frequency was measured with a Hewlett-Packard, Model 5233L, electronic counter. This is a solid-state device with a visual display of frequency.

Experimental Procedure

The general procedure for obtaining quantitative data was, with few exceptions, the same for any liquid employed in the tubes. The following steps constitute a typical test run:

1. The tube was filled to a level which was measured by a grid marked on a piece of aluminum inserted in the tube during the filling process.

2. The lowest resonant frequency giving stable operation was selected by observing the microphone output signal on the oscilloscope, the SPL meter reading, and the power input reading on the VAW meter. The most sensitive indication of the resonant condition was obtained by observation of the oscilloscope pattern of the SPL output signal from the test section.

3. The temperature was measured before a test and the thermometer removed (since any foreign object would create curtains at low power levels as explained in Chapter III). The temperature was again measured at the end of the test.

4. The power input to the test section was slowly raised while carefully observing the SPL meter. When the first curtain broke the surface in the tube, the SPL at the break was recorded. In the case of water, it was only necessary to observe the SPL meter for, when a curtain broke the surface, the SPL indication would drop immediately one to two db. However, when using acetone in the test section, the SPL meter was not sufficiently sensitive to the formation of curtains, since it did not drop a perceptible amount upon the formation of a curtain. This, of course, was due to the fact that water effectively blocked the tube when a curtain formed and acetone did not block the tube in all cases. It thus required assistance during the acetone tests in order to carefully monitor the SPL at which curtains formed.

5. The frequency was changed and the procedure was repeated for other liquid levels, frequencies, tube diameters, and liquids.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The parametric correlation of the threshold of curtain formation should serve as a basic starting point for further quantitative studies of the behavior inside the Kundt's tube. Not only does it give a correlation for the Kundt's tube containing a liquid, but it also implies the possibility of employing a similar technique to quantify the various phenomena observed in a Kundt's tube containing dust. Further, and more important, it indicates the possibility of quantifying the occurrence of the various vortex formations and behavior modes observed in tubes and channels over the past one hundred years. Equipment similar to that employed in this research can be used to determine some of the quantities only estimated in the past, e.g., particle velocity and intensity. The important factor in this improved experimental approach is the measurement of the sound pressure level in the tube.

The many observational details should be of value to future researchers in the area of acoustics in closed systems, especially in evaluating whether analytical studies correctly predict the actual behavior in a Kundt's tube containing a liquid.

The desalinization studies indicate a possibility, however remote, of employing the resonant tube to desalinate sea water or to separate mixtures upon the addition of refinements of technique or in conjunction with additional aids to desalinization. Even though this research did not find this line of study profitable, the salt deposits of Figure 29 should create further interest in desalinization or separation of mixtures.

Recommendations

As this research progressed additional lines of study unfolded. Many areas for further study became apparent from a study of the literature, primarily because of the inability of previous researchers to determine the exact conditions inside their test sections and also because of their power limitations. Many of the recommendations therefore stem from the recent availability of equipment capable of producing high intensities in tubes and also the availability of equipment capable of accurately measuring these intensities. Other recommendations stem from observations made during the course of this research. Certain minor refinements and studies have been mentioned or implied in the previous chapters of this dissertation; therefore, only the major recommendations will be given here. They are:

1. A method of correlating N/N_p versus SPL should be devised in order to predict not only the threshold of curtain formation as was done herein but also the formation of more than one curtain at a given resonant frequency. The blockage of the tube by the formation of the first curtain currently precludes an accurate correlation of this phenomenon. However, it appears that the SPL in the tube could be related to the power input for a given set of conditions and this then used to determine indirectly the values of SPL when additional curtains form. This might be accomplished by relating the power input to SPL before curtains

form and extrapolating this relation to higher values of SPL. It is also possible that taps in the tube wall between the curtains and the driver could be employed with proper calibration to give the tube SPL when curtains form.

2. A means of studying the vortex cells above the liquid should be devised. Either a fluid that would not absorb the smoke too rapidly to allow meaningful observations and photography should be found, or a means whereby the fluid itself produced a vapor that allowed observations should be devised. It would be of considerable interest to observe the exact nature of the vortex formation in the tube at the instant curtains are formed.

3. Many of the experiments of Andrade[11,12] should be repeated and the sound pressure measured as each of the phenomenon occurs. This should give added insight into the effects of vibrations in the tube.

4. Experiments to prove conclusively whether or not the basic change in vortex formation first observed by Jackson and Johnson[13] is a result of convective currents alone as has been proposed or is actually a manifestation of the excitation of a new mode of vibration as contended in this dissertation would be of interest. If it is concluded that a new mode of vibration has been excited, then steps should be taken to determine whether these modes would bring further changes in the behavior inside the tube.

5. The deposits of tobacco smoke in the resonant tube and the apparent filtering carried out in this manner suggest the possibility of an acoustic filter for air and other gases. Even though it appears that such a filter would be expensive to operate, there might be an application

that warrants the cost. For example, the acoustic force field might be employed on a space craft where ordinary force fields are absent for normal precipitation.

6. An investigation of the disorienting effects of a combination of sound and a stroboscopic light should be undertaken. This recommendation stems from the fact that, during the course of this research, a strobe light of variable frequency was employed to observe the liquid curtains and drops. Many times, after long periods of such observations, the writer became disorientated and dizzy. This disorientation was not noticeable until the writer would attempt to rise from his chair. At that time it was often difficult to determine the location of the light switch and to walk to the switch. The sensation passed quickly.

7. Extension of this research to very large tubes should be undertaken in order to determine the height to which curtains can be made to carry. The power requirement will be considerable for such a study. In fact, studies at the power levels necessary to determine the height to which the liquid can be made to carry would very likely necessitate the design of a special acoustical driver, or a series of such drivers.

APPENDIX A

PRESSURE DISTRIBUTION

General Remarks

Four different methods of determining the pressure difference between a node and an antinode in a resonant, closed channel and tube are now available. All four of these methods for calculating the pressure difference are basically identical in that they yield essentially the same answer for the pressure difference. First, there is the solution given by Howatson[26] in which he solved Euler's equation for the pressure difference and took the maximum particle velocity as the root-mean-square of the average particle velocity estimated at the antinode. Howatson did not obtain satisfactory agreement between his calculated and observed values for the pressure difference. However, it is now established that this disagreement was the result of an inaccuracy in estimating particle velocity and not the result of an inaccuracy in his equation. The second method for determining the pressure difference is based on first order acoustic phenomena, the expression for which is given in a later section. The third and forth methods for determining the pressure difference are solutions to the acoustical equations in a rectangular channel and in a tube given by Dr. K. R. Purdy[30]. Purdy's solutions are general solutions for the cases of the channel and the tube and give not only the pressure difference between a node and an antinode but also the general pressure distributions in these geometries as a function of tube length in the form of the variable x/λ. An expression for the number of crests in a resonant tube, the first order pressure solution to the acoustical equations, the results of Purdy's solution for the channel and the tube and, finally, a comparison of the measured value of pressure difference with the values calculated with both the first order acoustical results and Purdy's solution are given.

Preliminary Calculations

Before obtaining the pressure distribution in the tube, it is of interest to determine the number of points, N_p, at which a tube of length L can form crests and curtains.

In Chapter I it is shown that the wave length is given by the expression:

$$\lambda = c_\infty / f \quad . \tag{A-1}$$

Now, since there are two nodes and two antinodes per wave length, the number of crests forming in a resonant tube (a crest forms at each antinode), is given by

$$N_p = 2\ L/\lambda = 2\ L\ f/c_\infty \ . \tag{A-2}$$

Due account must be made in the calculation of N_p when the tube length is not an integral number of half wave lengths.

First Order Pressure Equation

The pressure distribution for first order acoustic phenomena can be obtained by substituting the velocity distribution obtained by first order calculations into the momentum equation giving

$$\rho_\infty \frac{\partial u'}{\partial t} + \frac{\partial p'}{\partial x} = 0 \; . \tag{A-3}$$

This yields

$$\frac{\partial p'}{\partial x} = \rho_\infty \, U_o \, \omega \cos(\frac{\partial x}{c_\infty}) \, \sin(\omega t) \tag{A-4}$$

and, upon integrating,

$$p' = -\rho_\infty \, c_\infty \, U_o \, \sin(\frac{\omega x}{c_\infty}) \, \sin(\omega t) \tag{A-5}$$

Substituting the latter expression into the relation for pressure as obtained in Chapter I, i.e., Equation 1-5b, yields the general first-order pressure distribution

$$p = p_1 - \rho_\infty \, c_\infty \, U_o \, \sin(\frac{\omega x}{c_\infty}) \, \sin(\omega t). \tag{A-6}$$

The absolute value of the maximum amplitude of the pressure wave at any given point in the tube is then

$$\left| p' \right| = \rho_\infty \, c_\infty \, U_o \, \sin(\frac{\omega x}{c_\infty}) \; , \tag{A-7}$$

and at any given point in the tube the pressure varies from its maximum to its minimum value in accordance with the function $\sin(\omega t)$.

The actual maximum and minimum values of the pressure will occur at the pressure antinodes (i.e., at the velocity nodes referred to throughout this dissertation simply as nodes). The absolute maximum or minimum value of the pressure deviation is simply

$$P_{\substack{max\\min}} = \rho_\infty \, c_\infty \, U_o \quad . \tag{A-8}$$

Therefore the maximum particle velocity is given by:

$$U_o = \frac{P_{max}}{\rho_\infty \, c_\infty} \quad , \tag{A-9}$$

where U_o has been related to the maximum value of the pressure amplitude since, as explained in Appendix B, P_{max} is related to SPL through the equation

$$P_{max} = 10^{\frac{(SPL-124.6)}{20}} \quad . \tag{A-10}$$

The expression for the velocity head is, of course, given by

$$\Delta p = (1/2) \, \rho_\infty \, U_o^2 \quad . \tag{A-11}$$

Measurement of the SPL in the tube and the air temperature is therefore sufficient to determine the difference in height from trough to crest.

Purdy's Second Order Pressure Equations

Briefly, the pressure distribution equations of Purdy consists of solving Equation (B.21) of Reference 5 for the time-mean pressure distribution in a rectangular channel and a similar equation for the time-mean pressure distribution in a tube. The result for the channel is

$$\overline{p}(x,y)-\overline{p}(0,y) = (1/4) \, \rho_\infty \, U_o^2 \, [1 - \cos(4\pi x/\lambda)] \quad , \tag{A-12}$$

and the result for the tube is of exactly the same form, viz.

$$\bar{p}(r,x)-\bar{p}(r,0) = (1/4)\ \rho_\infty U_o^2\ [1 - \cos(4\pi x/\lambda)]. \qquad \text{(A-13)}$$

In both cases

$$U_o = c_\infty\ [0.2\ C_p\ 10^{\frac{(SPL-180)}{20}}]\ , \qquad \text{(A-14)}$$

and

$$C_p \equiv 29.92/p_\infty \qquad \text{(A-15)}$$

if p_∞ is measured in inches of mercury.

Actually, the mean pressure difference does involve terms containing the frequency, but these terms are completely negligible with regard to the terms given in Equations (A-12) and (A-13), especially at the frequencies in the range of this research. The equations for the mean pressure difference also involve y and r in the channel and tube, respectively. Since the fluid is air and the tubes are never larger than three inches in this research, any consideration of a pressure variation with y or r is omitted.

Discussion of Pressure Results

The pressure distribution solutions obtained by Purdy, unlike the results for velocity, indicate that the pressure is not affected appreciably by higher order acoustical effects. If this were true in the case of the velocity there would be no vortices formed in the tube. Table 1 shows a comparison of several values of the pressure head predicted by both the first-order acoustic equation and by Purdy's equation, with the liquid head actually measured. Considering the error that can be expected from the measurements with the traveling microscope, the error of $\pm$ 1.5 db. estimated for SPL measurements and the fact that surface tension will likely play a part in the height of the liquid, the agreement is excellent.

It should be pointed out that Howatson was disappointed in his calculated and measured results in a similar experiment. However, Howatson had to estimate the maximum particle velocity at the antinode by observing its value at another point and calculating the value it would have at the antinode. A value in excess of 162 db. is obtained when Equations (A-9) and (A-10) are employed in reverse to determine the value of SPL that would have been necessary to produce Howatson's estimated value of particle velocity. Considering Howatson's equipment, it appears unlikely that he could obtain a value this high. If equipment capable of measuring SPL had been available to Howatson, he likely would have realized this, and it is likely that he would have obtained close agreement between his calculated and measured values of liquid height.

Table 1. Comparison of Calculated and Measured Pressure Head.

Frequency cps	Liquid	Temp. ^{o}F	SPL db.	First Order Prediction inches	Purdy's Second Order Prediction inches	Measured Press. Difference inches
429	Acet.	76	156.8	0.0684	0.0691	0.0748
507	Acet.	76	151.0	0.0180	0.0182	0.0197
688	Acet.	76	146.5	0.00637	0.00644	0.00591

APPENDIX B

CALCULATION AND TABULATION OF RESULTS

Typical results from the experimental program are presented in Tables 2 and 3. All were obtained using the experimental equipment and procedures described in Chapter V.

In order to calculate the results for the final correlation of threshold data shown in Figure 36 and presented in the final two columns of Table 3, it was necessary to perform a dimensional analysis of the variables governing the behavior in the Kundt's tube partially filled with water. This dimensional analysis is given in Appendix C.

The values of P_{max} were obtained from the data on sound pressure level, SPL, in the tube. The SPL value is related to P_{max} by

$$SPL = 20 \log(P/2 \times 10^{-4}) \text{ db} , \tag{B-1}$$

where the pressure is referred to 0.0002 microbars and P is the r.m.s. pressure deviation in the resonant tube. The r.m.s. pressure, P, is related to P_{max} by

$$P = \frac{\sqrt{2}}{2} P_{max} . \tag{B-2}$$

Converting the pressure to pounds per square foot and substituting for P yields

$$SPL = 20 \log P_{max} + 124.57 \text{ db}, \tag{B-3}$$

where P_{max} is measured in psf. solving this expression for P_{max} yields

$$P_{max} = 10^{\frac{SPL - 124.6}{20}} . \qquad (B-4)$$

The calculated and measured results are shown in Table 2 for the formation of multiple curtains. These data are plotted in Figure 34 of Chapter IV. The calculated and measured results for the "threshold" of formation of curtains for various resonant frequencies, tube diameters and two liquids are given in Table 3 and presented in Figure 26 of Chapter IV. In addition, the data for Figure 35 of Chapter IV were taken from Table 3.

The error band shown in Figure 36 of Chapter IV was obtained from the estimated error in the SPL measurements. Although the estimated error is $\pm$ 1.5 db., the resulting error on the plot does not yield an equal error band for positive and negative errors. This can be seen by the following calculation of the positive and negative errors: The positive error is given by

$$\left.\frac{P_{max\ error}}{P_{max}}\right|_{pos.} = 10^{\frac{+1.5}{20}} = 1.1885 \qquad (B-6)$$

or an error of +18.85 per cent. The negative error is given by

$$\left.\frac{P_{max\ error}}{P_{max}}\right|_{neg.} = 10^{\frac{-1.5}{20}} = 0.8415 \qquad (B-7)$$

or a negative error of -15.85 per cent. This difference in the error band is reflected in Figure 36.

Table 2. Multiple Curtain Formation Data for Water

Frequency cps	Water Level Ratio d/D	Curtains Formed N	Curtains Possible N_p	Power Input Watts	Curtain Ratio N/N_p
662	0.10	1	4	44.3	0.25
		2		61.3	0.50
		3		78.2	0.75
		4		99.0	1.00
662	0.33	1	4	40.3	0.25
		2		49.1	0.50
		3		57.5	0.75
		4		66.3	1.00
825	0.10	1	5	36.8	0.20
		2		41.2	0.40
		3		43.1	0.60
		4		47.6	0.80
		5		51.3	1.00
825	0.33	1	5	30.6	0.20
		2		35.3	0.40
		3		39.2	0.60
		4		42.0	0.80
		5		45.9	1.00

Table 3. Curtain Formation - Threshold Data

Frequency cps	Sound Press. Level db.	P_{max} psf	Wave Length ft.	$\frac{P_{max}\ \mu^2}{\rho\ \sigma^2}$ $\times 10^{-5}$	$\frac{\rho\ \sigma\ \lambda}{\mu^2}$ $\times 10^{-5}$
WATER					
Tube I.D. = 1-1/8 inches; T=80°F					
400	158.2	47.9	2.850	33.10	8.38
668	153.7	28.16	1.705	19.94	5.02
733	149.4	17.40	1.555	18.94	4.57
901	146.4	12.30	1.265	8.50	3.72
1068	143.5	8.91	1.066	6.16	3.14
1236	140.6	6.31	0.921	4.36	2.71
Tube I.D. = 1-3/4 inches; T=80°F					
360	164.8	77.6	3.165	53.65	9.31
515	156.4	39.4	2.211	27.23	6.51
694	152.3	24.58	1.642	16.99	4.83
841	148.8	16.23	1.355	11.21	3.98
1013	145.5	11.10	1.123	7.68	3.30
Tube I.D. = 2-3/4 inches; T=82°F					
376	160.4	61.65	3.034	40.90	9.32
540	154.6	31.62	2.112	21.00	6.48
692	150.0	18.64	1.650	12.35	5.06
850	146.6	12.60	1.343	8.36	4.12
ACETONE					
Tube I.D. = 1-3/4 inches; T=78°F					
298	162.6	79.40	3.787	91.00	11.62
429	155.0	23.11	2.630	26.51	8.07
507	150.1	18.85	2.227	21.61	6.84
689	146.6	12.60	1.639	14.45	5.03
883	143.1	8.41	1.279	9.64	3.92
932	139.9	5.82	1.211	6.68	3.72
1015	136.9	4.12	1.112	4.72	3.41

APPENDIX C

FORMATION OF LIQUID CURTAINS - DIMENSIONAL ANALYSIS

When the investigation of curtain formation was first undertaken, many variables not included in the dimensional analysis of this section were considered to be pertinent to the investigation. As explained in Chapter IV, many of them were eliminated as the experimental program progressed and understanding and observation of the phenomena increased. For example, it was found that, although the power input to the tube necessary to form curtains was a function of tube diameter and water level, these variables could be omitted when tube SPL instead of power input was used as the variable related to energy input. Of course, the tube SPL is a function of power input, tube diameter and water depth, but it combines the consideration of these variables and therefore reduces the task of correlation. Tube length was also eliminated since, as explained in Chapter III, this variable does not have a first-order effect on curtain formation in tubes of the length employed in this research. It is clear, however, that tube length would become a factor for consideration in very long tubes.

The variables finally selected as being of importance in curtain formation along with their MLT units are

P_{max} - Maximum pressure deviation (amplitude), M/LT^2

f - Frequency, $1/T$

λ - Wave length, L

ρ - Density, M/L^3

σ - Surface tension, M/T^2

μ - Dynamic viscosity, M/LT

The pressure amplitude, P_{max}, can be written as a function of the remaining variables, i.e.

$$P_{max} = F\ (\rho,\ \sigma,\ \mu,\ \lambda)\ . \tag{C-1}$$

Next, it is assumed that P_{max} can be expressed as

$$P_{max} = C\ \rho^a\ \sigma^b\ \mu^c\ \lambda^d\ . \tag{C-2}$$

This equation written in terms of the dimensions of each variable then becomes

$$M/LT^2 = (M/L^3)^a\ (M/L^2)^b\ (M/LT)^c\ (L)^d\ . \tag{C-3}$$

Then, for dimensional consistency, the following equations must be satisfied:

$$\text{For M:}\ \ 1 = a + b + c \tag{C-4a}$$

$$\text{For L:}\ -1 = -3a - c + d \tag{C-4b}$$

$$\text{For T:}\ -2 = -2b - c\ \ . \tag{C-4c}$$

Solving these in terms of d yields

$$a = 1 + d;\ b = 2 + d;\ c = -2 - 2d\ . \tag{C-5}$$

Then, P_{max} can be written

$$P_{max} = C \left(\frac{\rho\ \sigma^2}{\mu^2}\right) \left(\frac{\rho\ \sigma\ \lambda}{\mu^2}\right)^n\ \ , \tag{C-6}$$

where n has replaced d as the exponent to avoid confusion with d as used to denote water depth.

The final dimensionless equation becomes

$$\left(\frac{P_{max}\ \mu^2}{\rho\ \sigma^2}\right) = C \left(\frac{\rho\ \sigma\ \lambda}{\mu^2}\right)^n \quad . \tag{C-7}$$

This equation was employed in the correlation of the data for the threshold of curtain formation as shown in Figure 36.

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